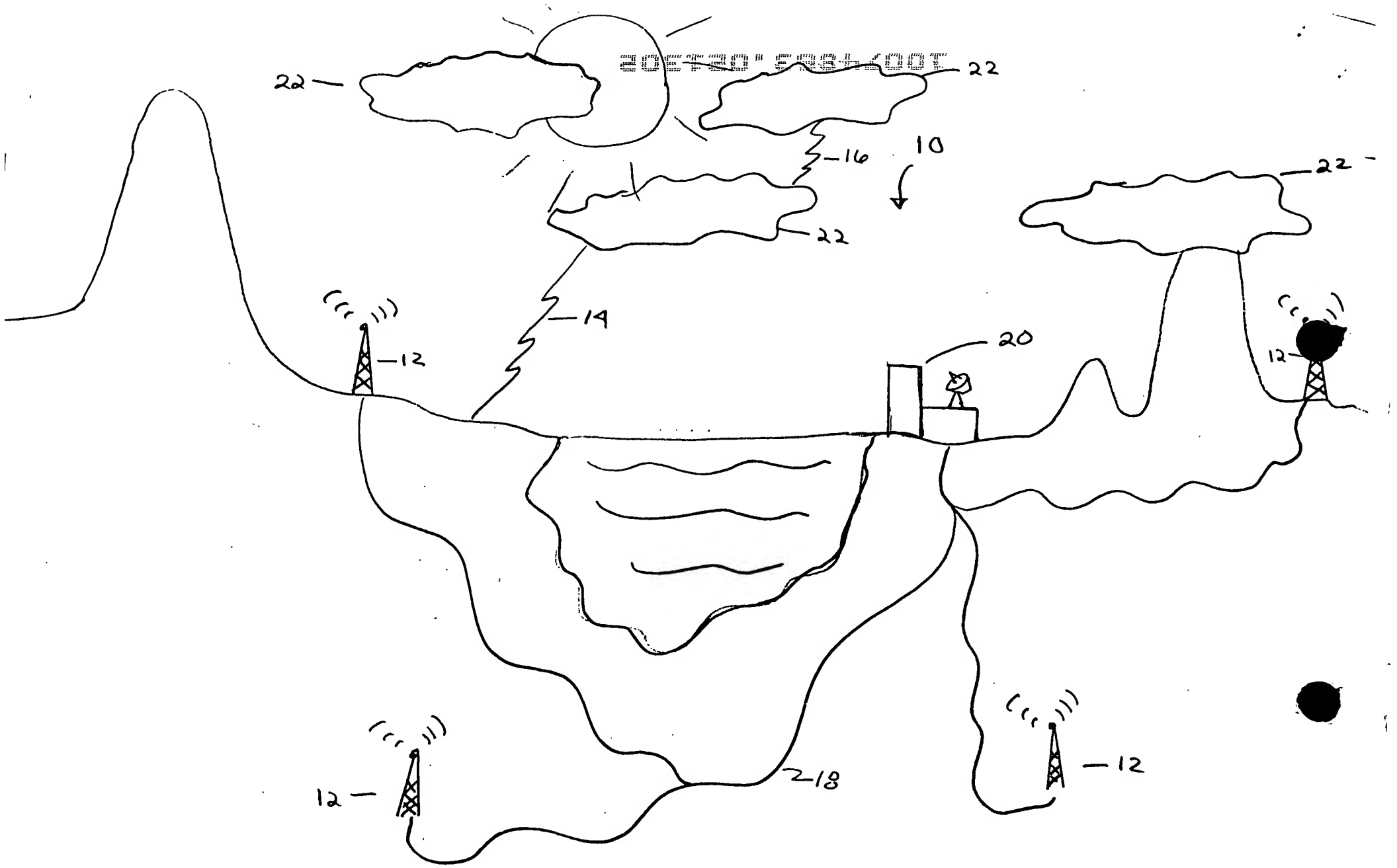

FIG. 1

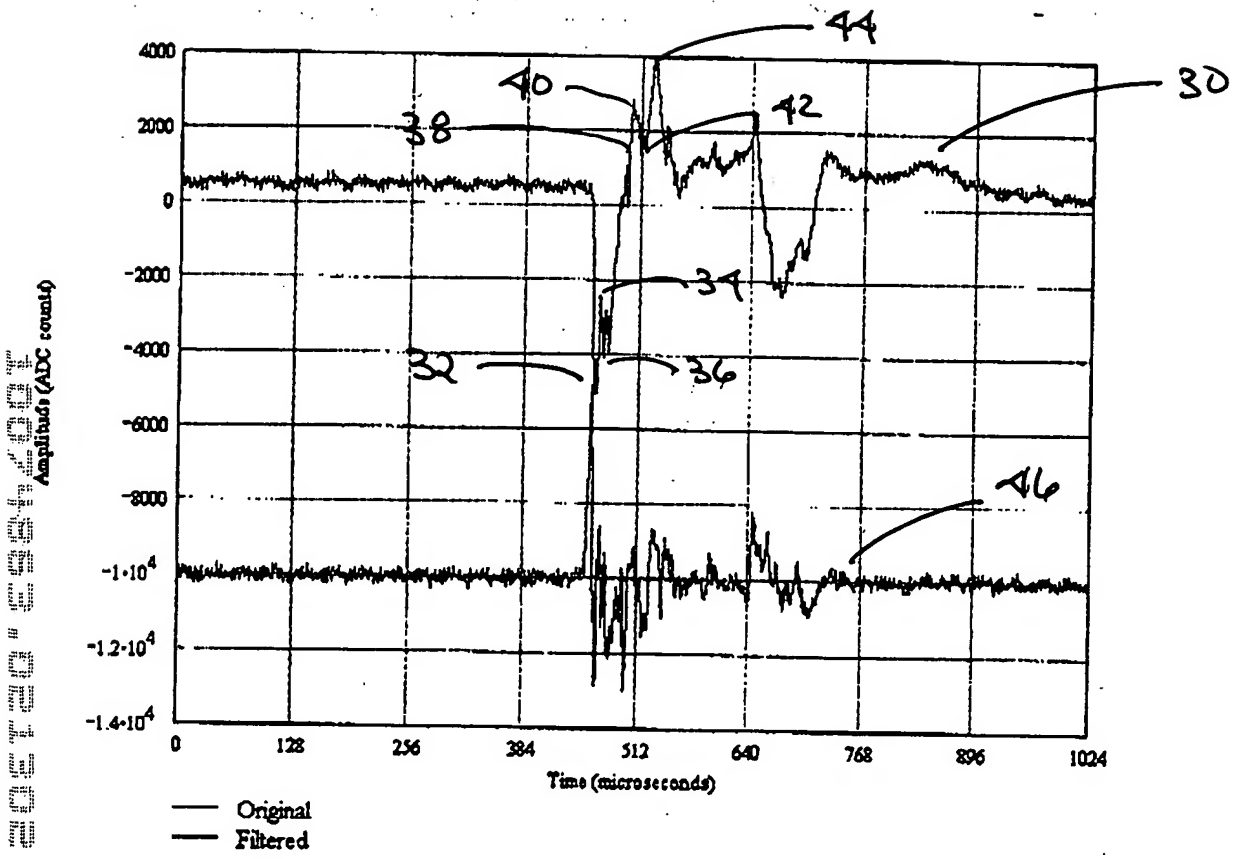
44
40
42
30
38
34
32
36
46
4000
2000
0
-2000
-4000
-6000
-8000
-1·10^4
-1.2·10^4
-1.4·10^4
0
128
256
384
512
640
768
896
1024
Amplitude (ADC counts)
Time (microseconds)
Original
Filtered

FIG. 2

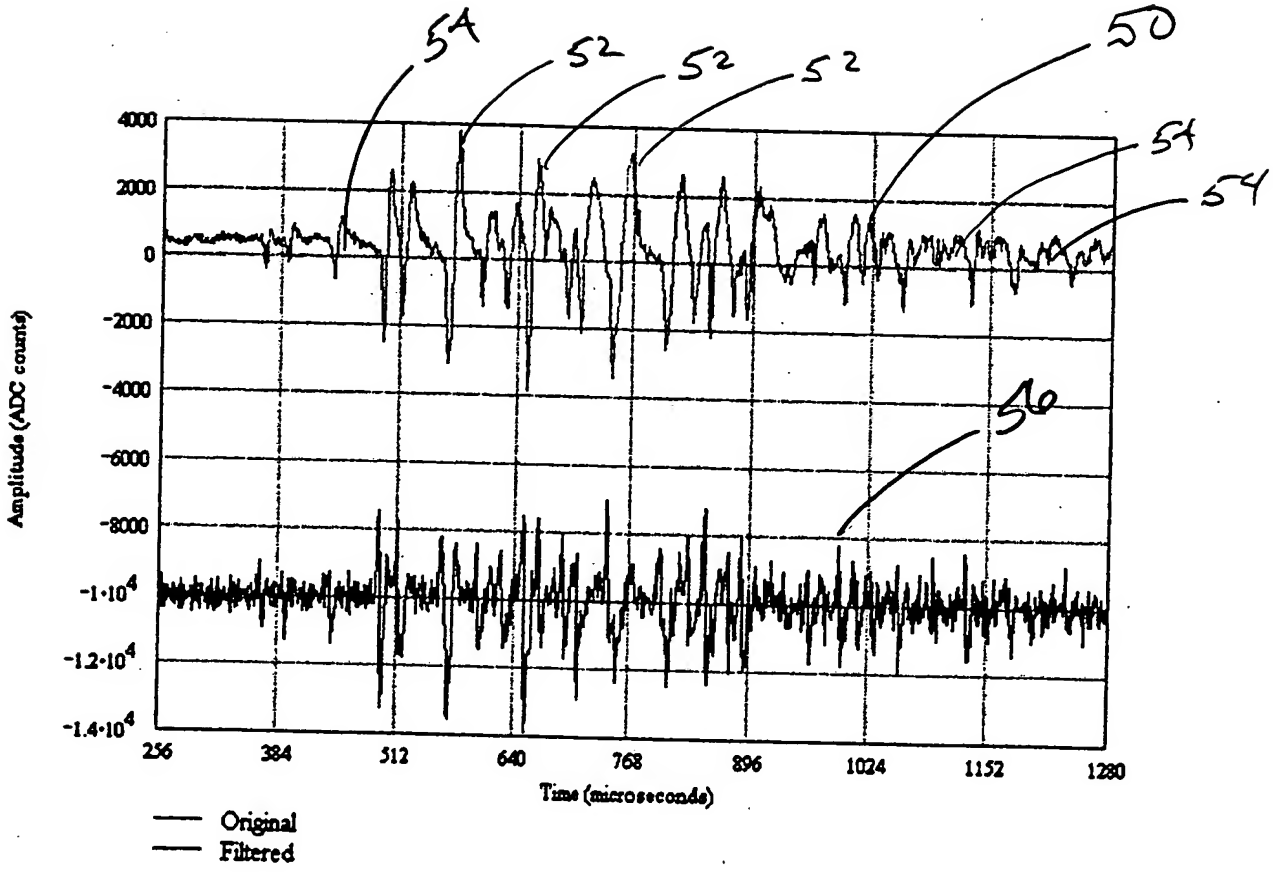
54
52
52
52
50
54
54
56
4000
2000
0
-2000
-4000
-6000
-8000
-1·10^4
-1.2·10^4
-1.4·10^4
Amplitude (ADC counts)
256
384
512
640
768
896
1024
1152
1280
Time (microseconds)
Original
Filtered

FIG. 3

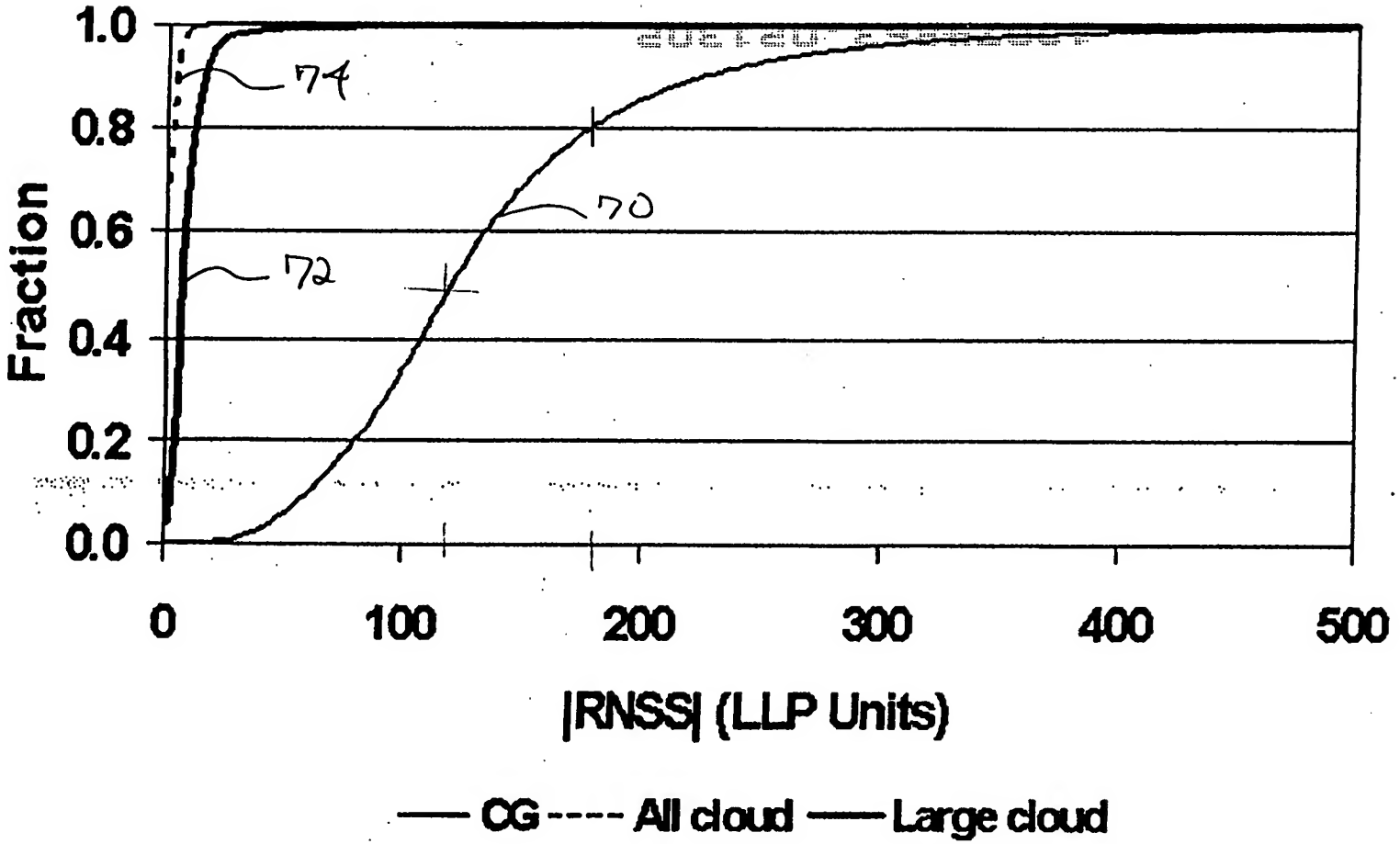
1.0
0.8
0.6
0.4
0.2
0.0
Fraction
74
70
72
0
100
200
300
400
500
|RNSS| (LLP Units)
CG
All cloud
Large cloud

FIG. 4

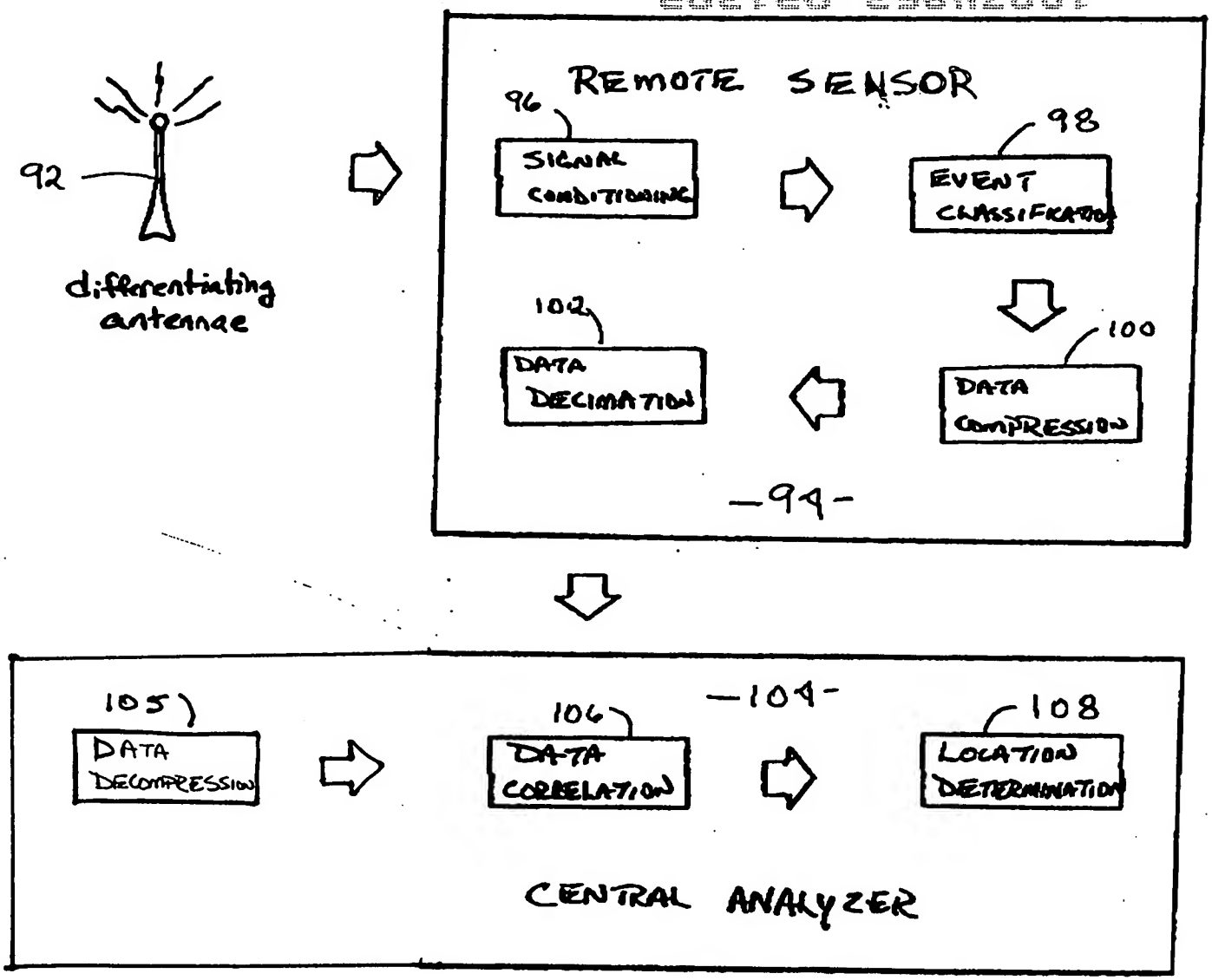
92
differentiating antennae
REMOTE SENSOR
96
SIGNAL CONDITIONING
98
EVENT CLASSIFICATION
100
DATA COMPRESSION
102
DATA DECIMATION
94
105
DATA DECOMPRESSION
106
DATA CORRELATION
104
108
LOCATION DETERMINATION
CENTRAL ANALYZER

FIG. 5

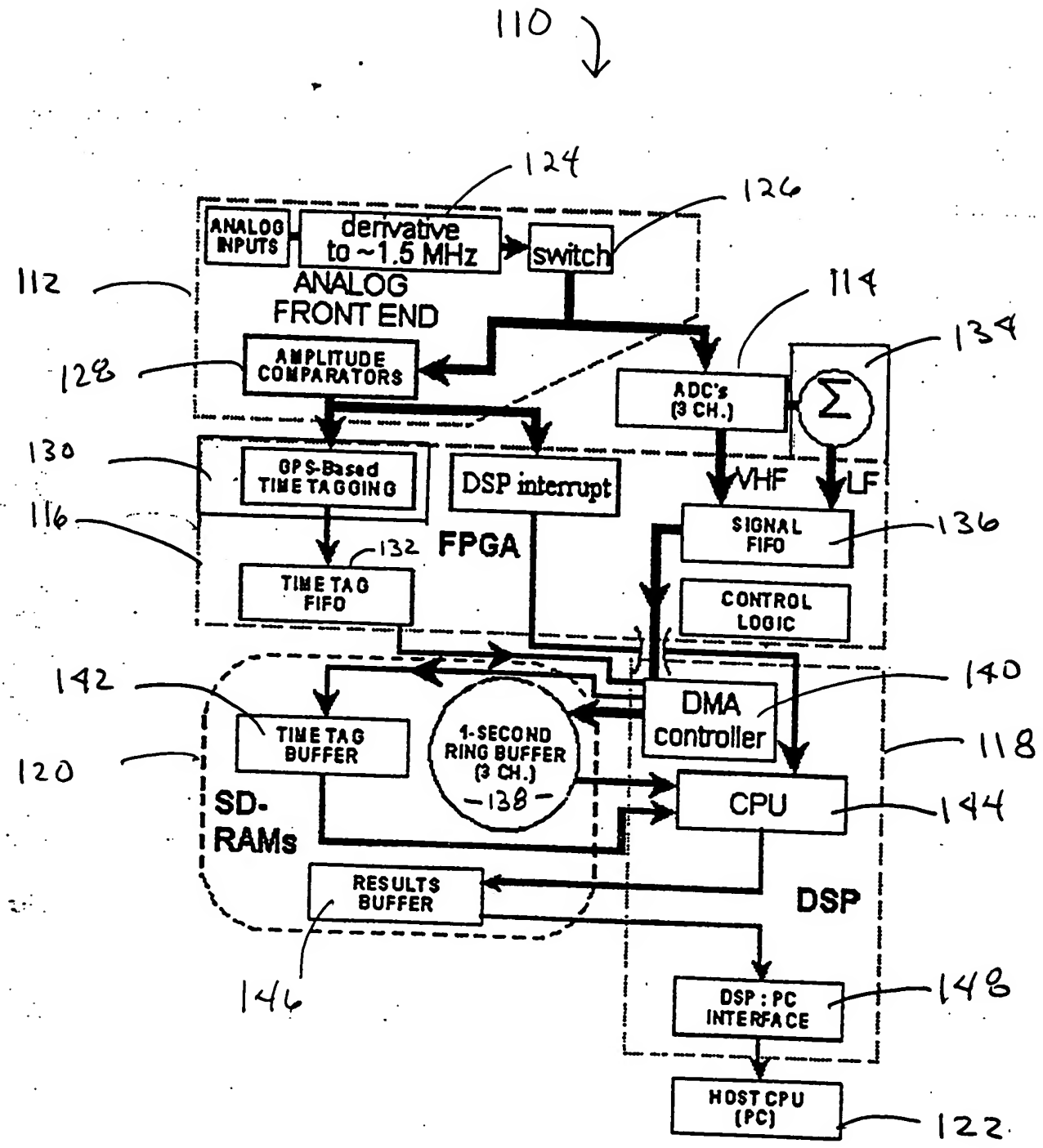
110
124
126
ANALOG INPUTS
derivative to ~1.5 MHz
switch
112
ANALOG FRONT END
114
134
128
AMPLITUDE COMPARATORS
ADC's (3 CH.)
Σ
130
GPS-Based TIME TAGGING
DSP interrupt
VHF
LF
116
132
FPGA
SIGNAL FIFO
136
TIME TAG FIFO
CONTROL LOGIC
142
140
DMA controller
TIME TAG BUFFER
1-SECOND RING BUFFER (3 CH.)
138
118
120
SD-RAMs
CPU
144
RESULTS BUFFER
DSP
146
DSP : PC INTERFACE
148
HOST CPU (PC)
122

FIG. 6

Major components of filtering & amplification

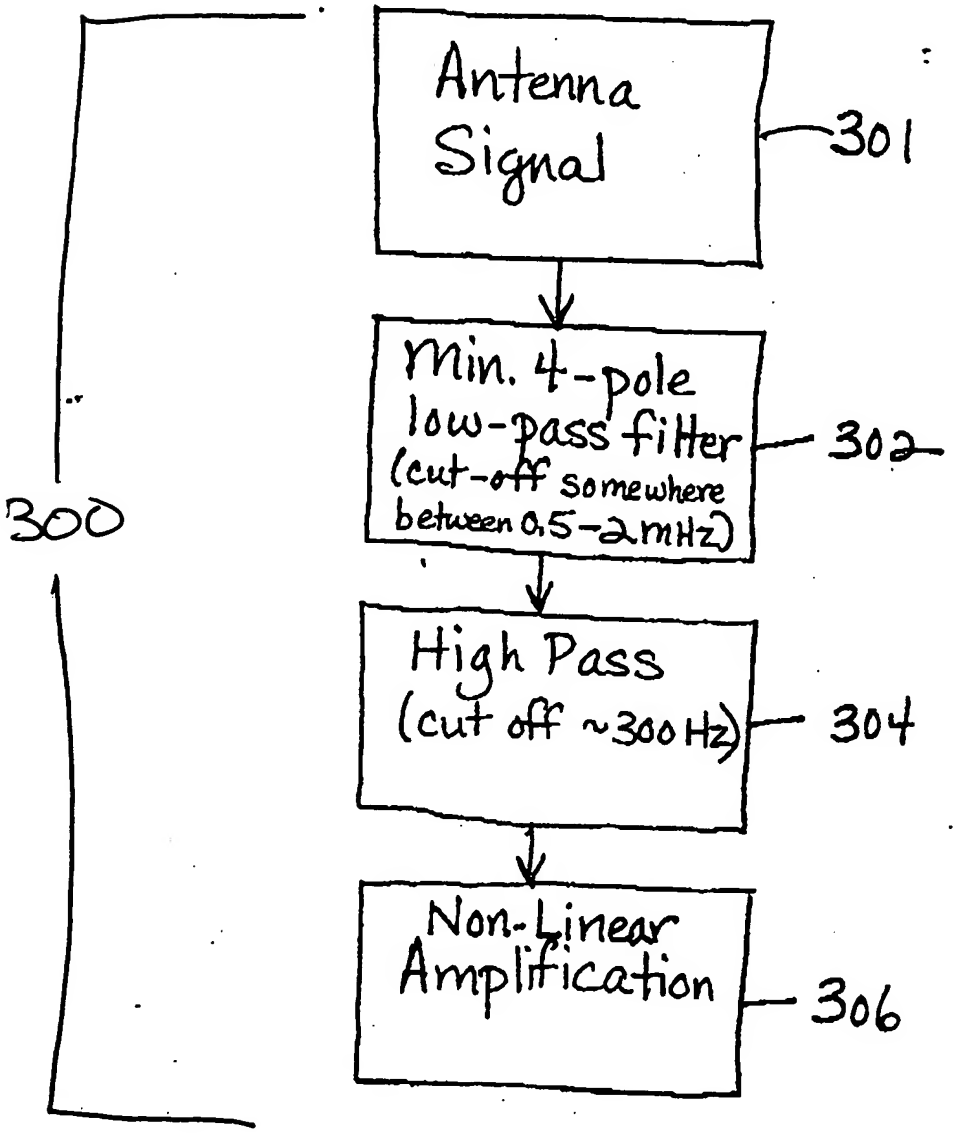

FIG. 7

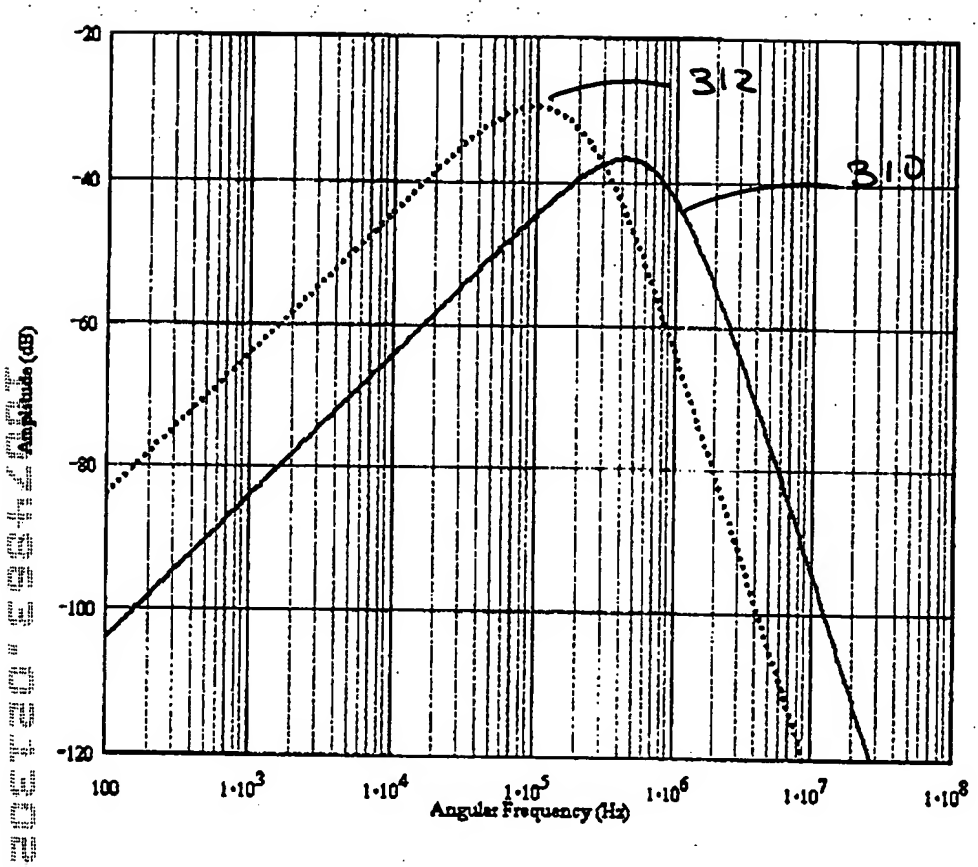
-20
-40
-60
-80
-100
-120
Amplitude (dB)
100
1·10^3
1·10^4
1·10^5
1·10^6
1·10^7
1·10^8
Angular Frequency (Hz)
312
310

FIG. 8

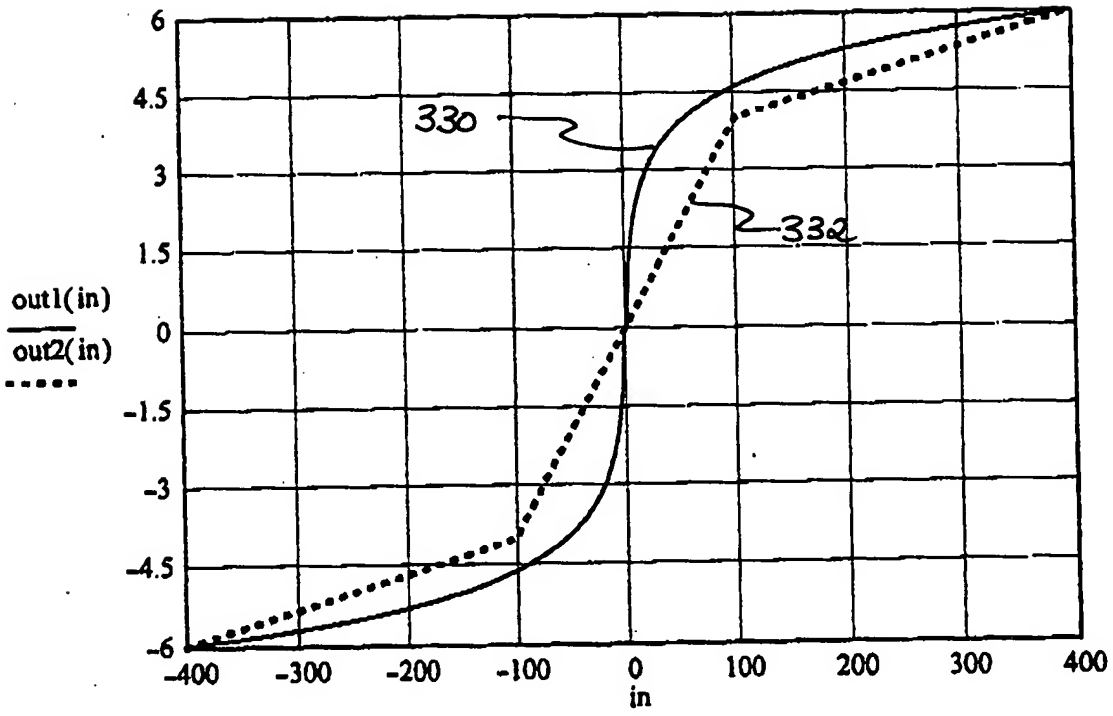
6
4.5
3
1.5
0
-1.5
-3
-4.5
-6
-400
-300
-200
-100
0
100
200
300
400
in
out1(in)
out2(in)
330
332

FIG. 9

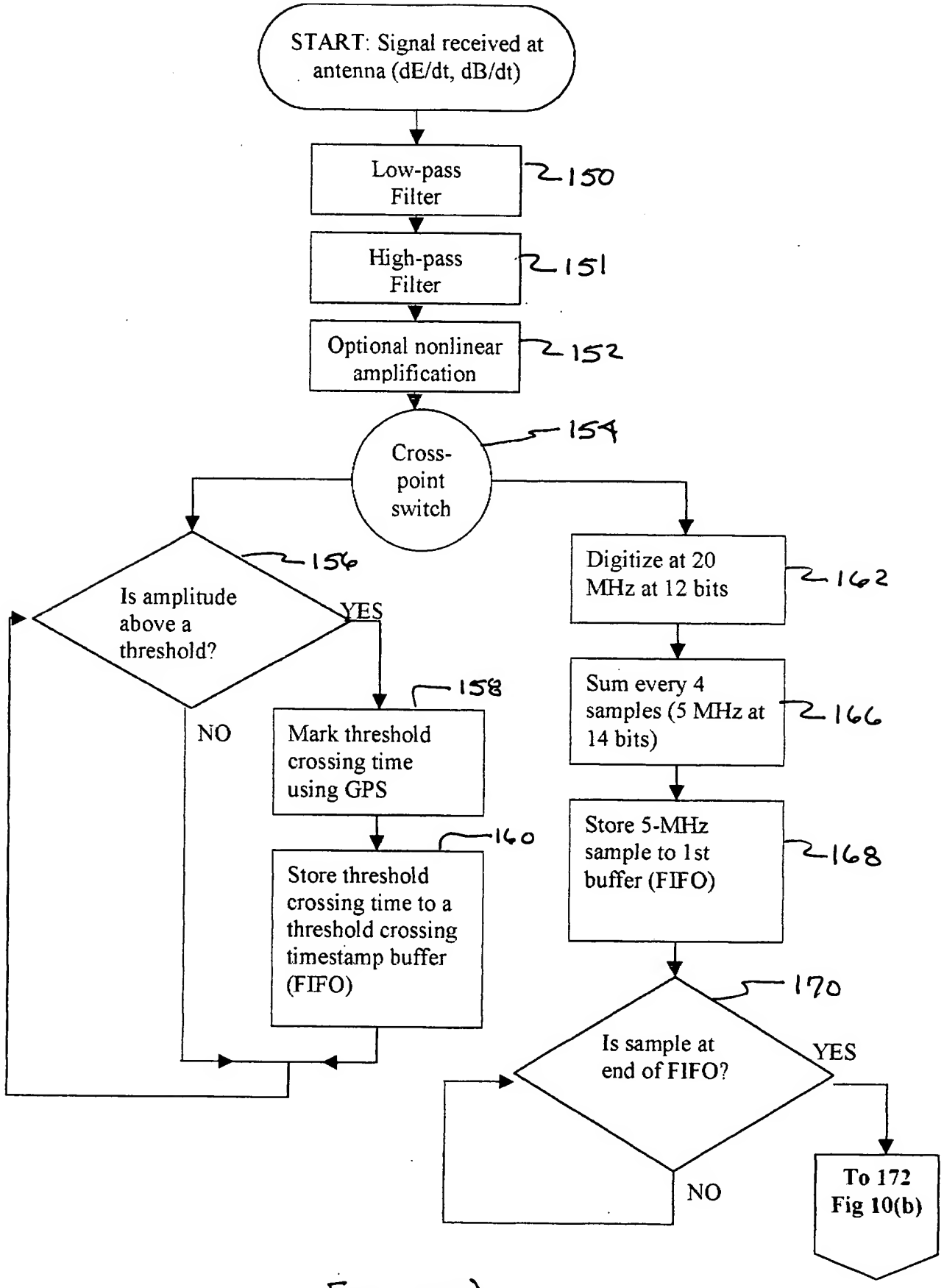
START: Signal received at antenna (dE/dt, dB/dt)
Low-pass Filter
150
High-pass Filter
151
Optional nonlinear amplification
152
Cross-point switch
154
Is amplitude above a threshold?
156
YES
NO
Mark threshold crossing time using GPS
158
Store threshold crossing time to a threshold crossing timestamp buffer (FIFO)
160
Digitize at 20 MHz at 12 bits
162
Sum every 4 samples (5 MHz at 14 bits)
166
Store 5-MHz sample to 1st buffer (FIFO)
168
Is sample at end of FIFO?
170
YES
NO
To 172 Fig 10(b)

Fig. 10(a)

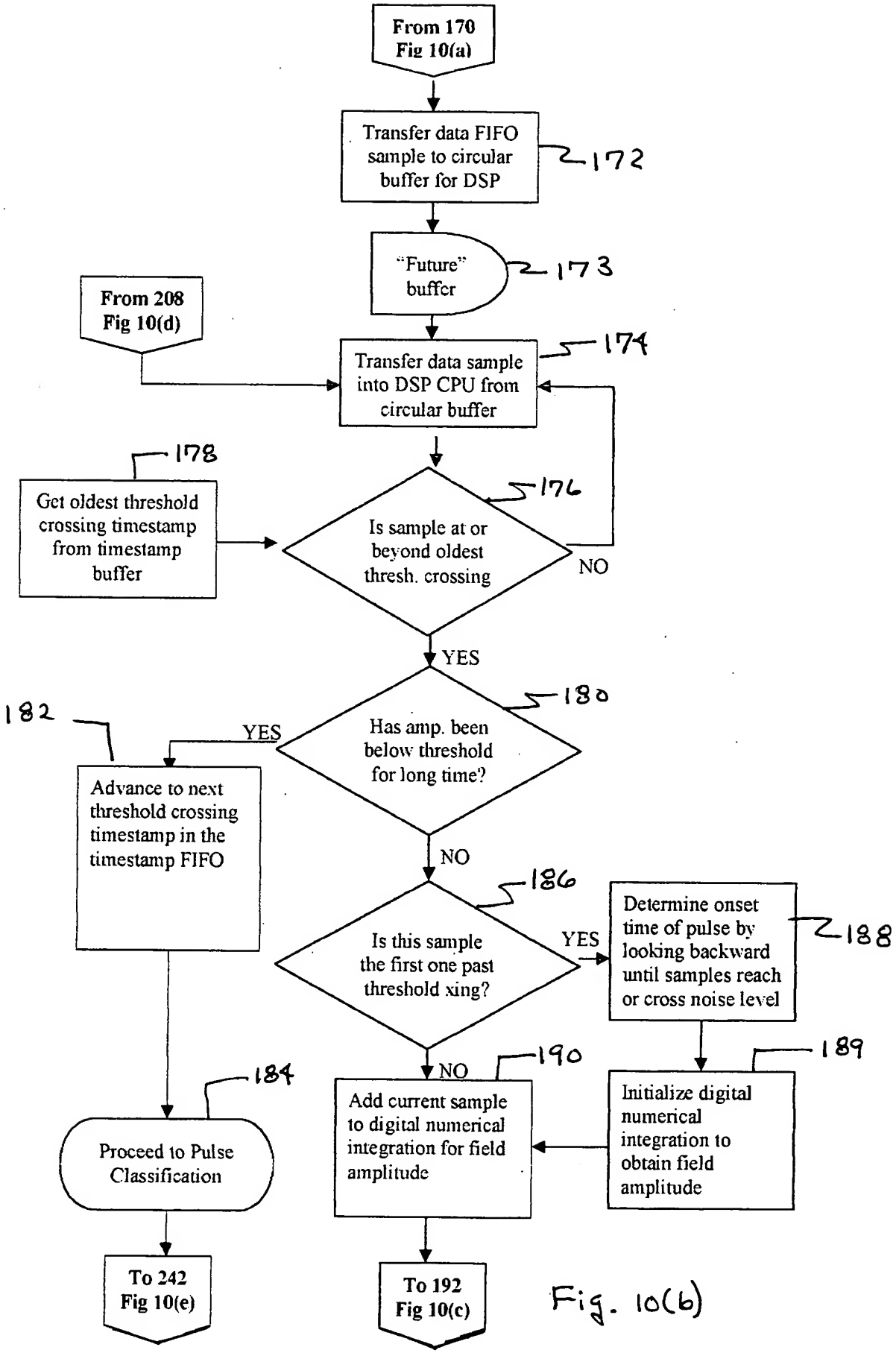
From 170 Fig 10(a)
Transfer data FIFO sample to circular buffer for DSP
172
"Future" buffer
173
From 208 Fig 10(d)
Transfer data sample into DSP CPU from circular buffer
174
178
Get oldest threshold crossing timestamp from timestamp buffer
Is sample at or beyond oldest thresh. crossing
176
NO
YES
180
182
YES
Has amp. been below threshold for long time?
Advance to next threshold crossing timestamp in the timestamp FIFO
NO
186
Is this sample the first one past threshold xing?
YES
Determine onset time of pulse by looking backward until samples reach or cross noise level
188
189
NO
190
Add current sample to digital numerical integration for field amplitude
Initialize digital numerical integration to obtain field amplitude
184
Proceed to Pulse Classification
To 242 Fig 10(e)
To 192 Fig 10(c)

Fig. 10(b)

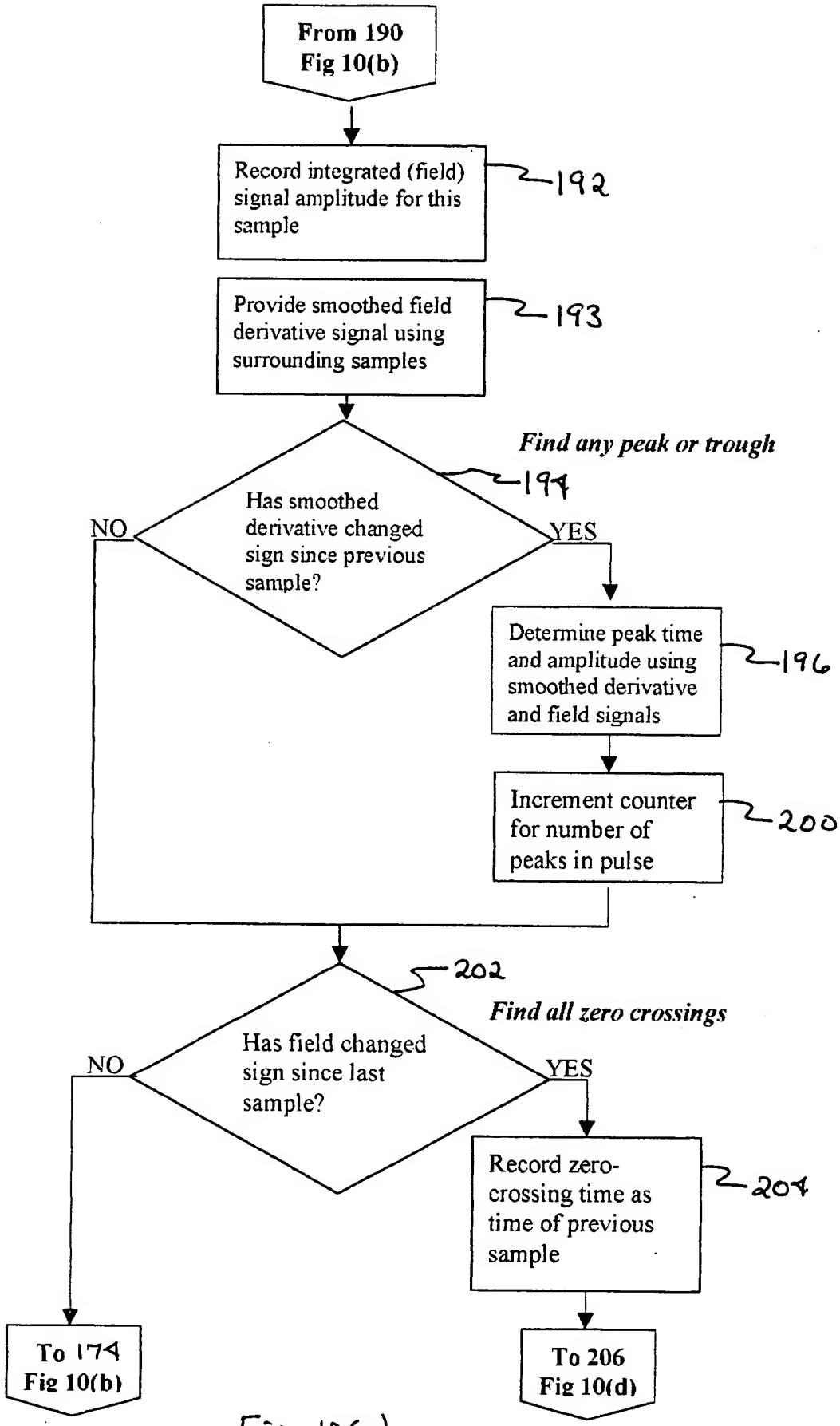
From 190
Fig 10(b)
Record integrated (field) signal amplitude for this sample
192
Provide smoothed field derivative signal using surrounding samples
193
Find any peak or trough
194
Has smoothed derivative changed sign since previous sample?
NO
YES
Determine peak time and amplitude using smoothed derivative and field signals
196
Increment counter for number of peaks in pulse
200
202
Find all zero crossings
Has field changed sign since last sample?
NO
YES
Record zero-crossing time as time of previous sample
204
To 174
Fig 10(b)
To 206
Fig 10(d)

Fig. 10(c)

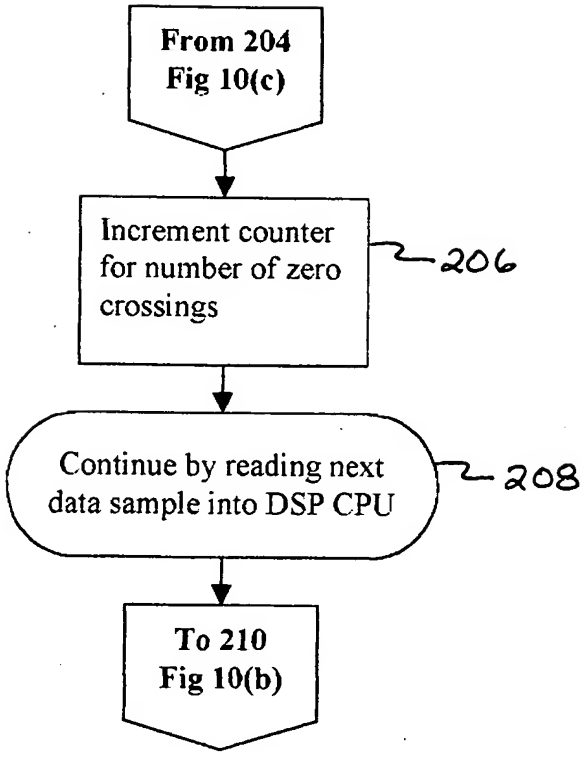
From 204
Fig 10(c)
Increment counter for number of zero crossings
206
Continue by reading next data sample into DSP CPU
208
To 210
Fig 10(b)

Fig. 10(d)

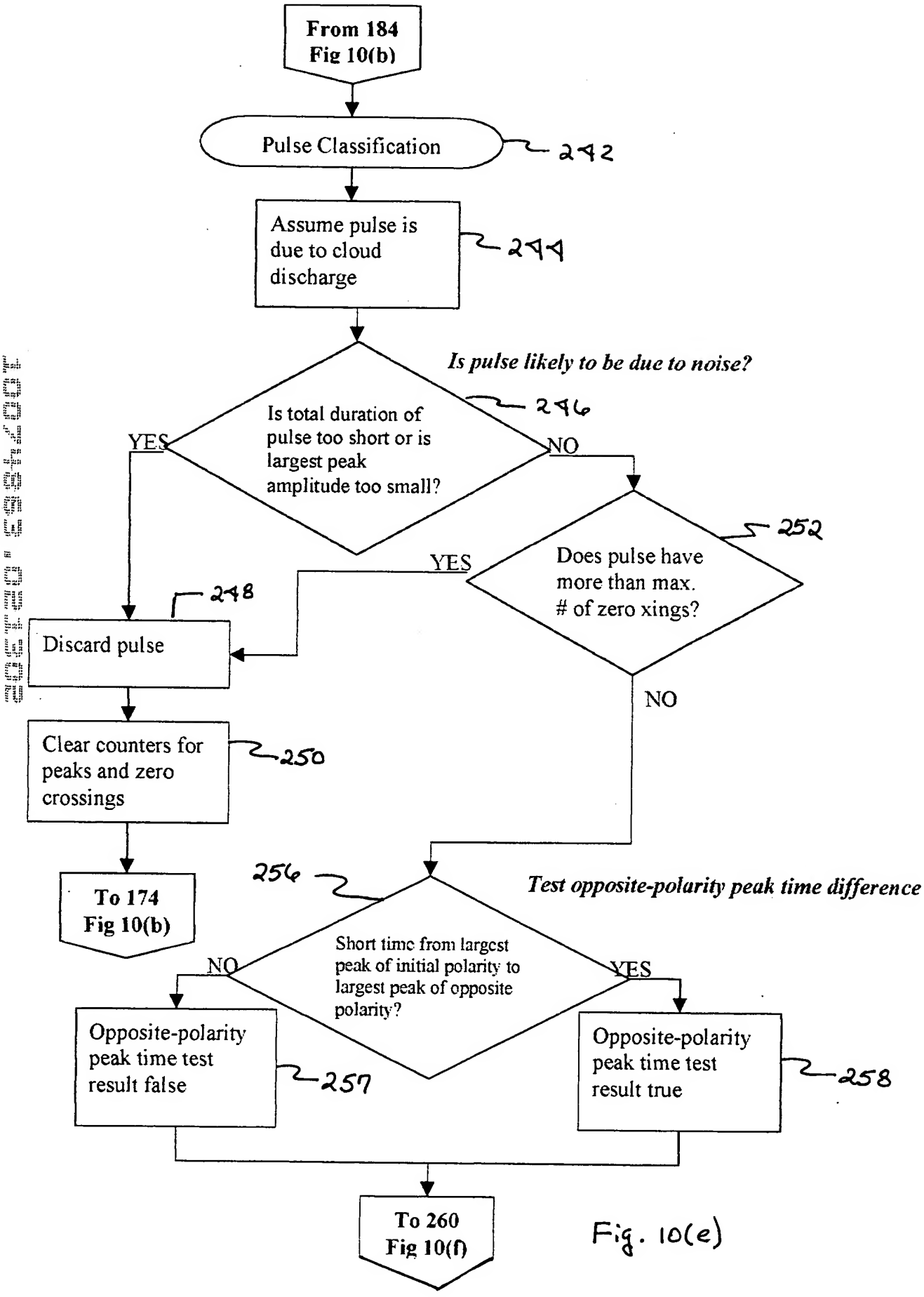
From 184
Fig 10(b)
Pulse Classification
242
Assume pulse is due to cloud discharge
244
Is pulse likely to be due to noise?
Is total duration of pulse too short or is largest peak amplitude too small?
246
YES
NO
Does pulse have more than max. # of zero xings?
252
YES
NO
Discard pulse
248
Clear counters for peaks and zero crossings
250
To 174
Fig 10(b)
256
Test opposite-polarity peak time difference
Short time from largest peak of initial polarity to largest peak of opposite polarity?
NO
YES
Opposite-polarity peak time test result false
257
Opposite-polarity peak time test result true
258
To 260
Fig 10(f)

Fig. 10(e)

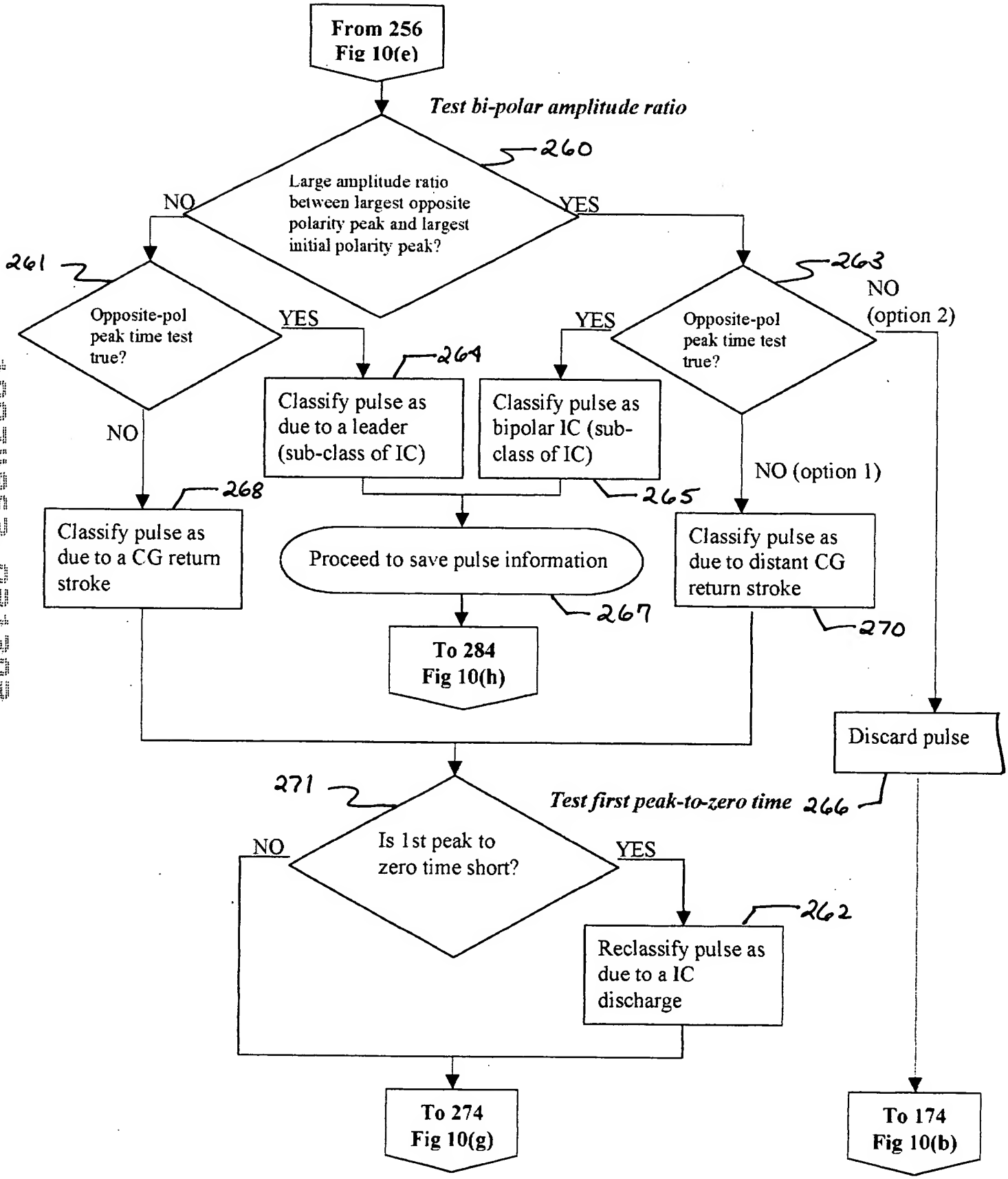
From 256
Fig 10(e)
Test bi-polar amplitude ratio
260
Large amplitude ratio between largest opposite polarity peak and largest initial polarity peak?
NO
YES
261
Opposite-pol peak time test true?
YES
NO
263
Opposite-pol peak time test true?
YES
NO (option 2)
264
Classify pulse as due to a leader (sub-class of IC)
Classify pulse as bipolar IC (sub-class of IC)
NO (option 1)
265
268
Classify pulse as due to a CG return stroke
Proceed to save pulse information
267
Classify pulse as due to distant CG return stroke
270
To 284
Fig 10(h)
Discard pulse
271
Test first peak-to-zero time
266
Is 1st peak to zero time short?
NO
YES
262
Reclassify pulse as due to a IC discharge
To 274
Fig 10(g)
To 174
Fig 10(b)

Fig. 10(f)

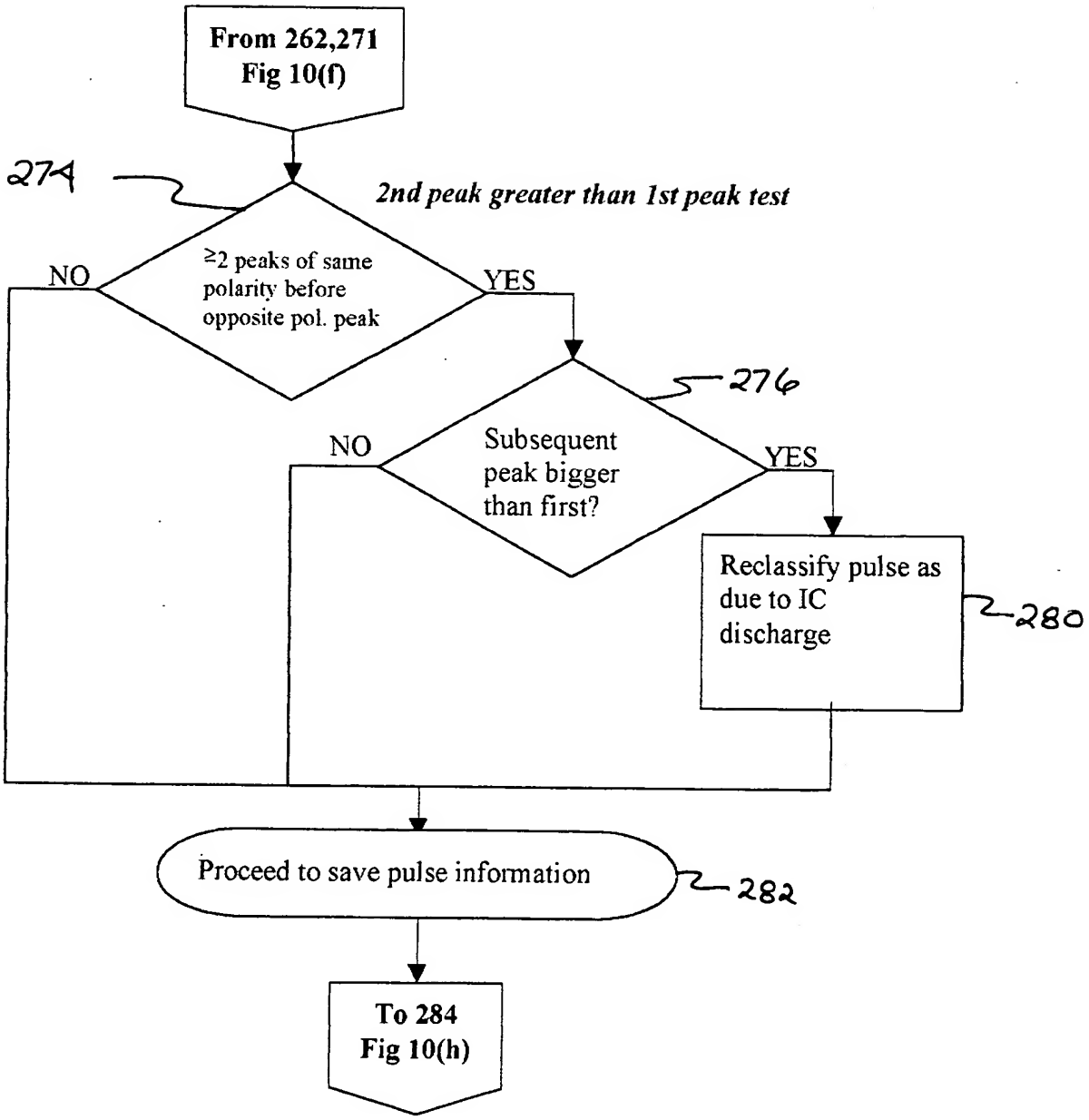
From 262,271
Fig 10(f)
274
2nd peak greater than 1st peak test
≥2 peaks of same polarity before opposite pol. peak
NO
YES
276
Subsequent peak bigger than first?
NO
YES
Reclassify pulse as due to IC discharge
280
Proceed to save pulse information
282
To 284
Fig 10(h)

Fig. 10 (g)

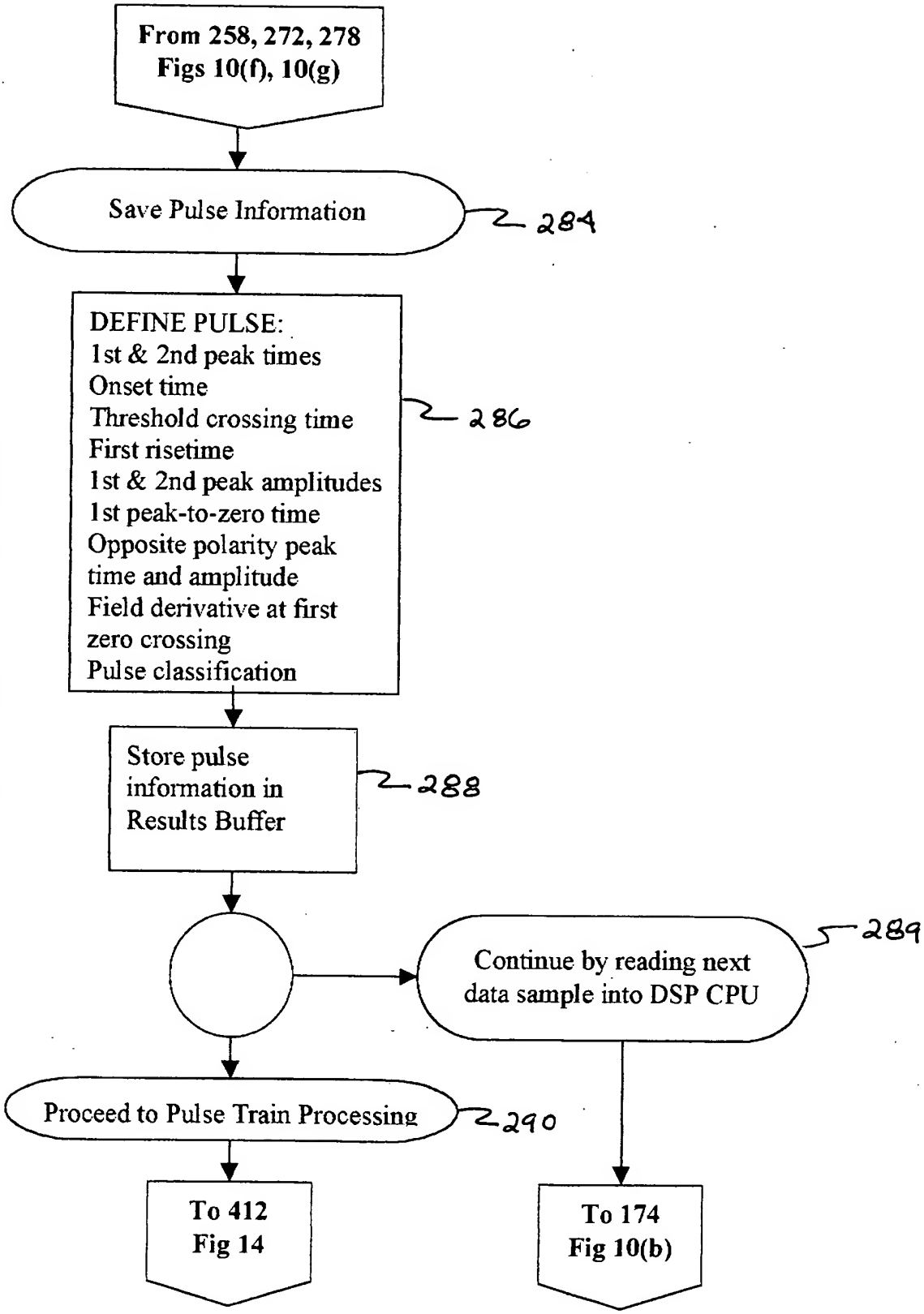
From 258, 272, 278
Figs 10(f), 10(g)
Save Pulse Information
284
DEFINE PULSE:
1st & 2nd peak times
Onset time
Threshold crossing time
First risetime
1st & 2nd peak amplitudes
1st peak-to-zero time
Opposite polarity peak time and amplitude
Field derivative at first zero crossing
Pulse classification
286
Store pulse information in Results Buffer
288
Continue by reading next data sample into DSP CPU
289
Proceed to Pulse Train Processing
290
To 412
Fig 14
To 174
Fig 10(b)

Fig. 10(h)

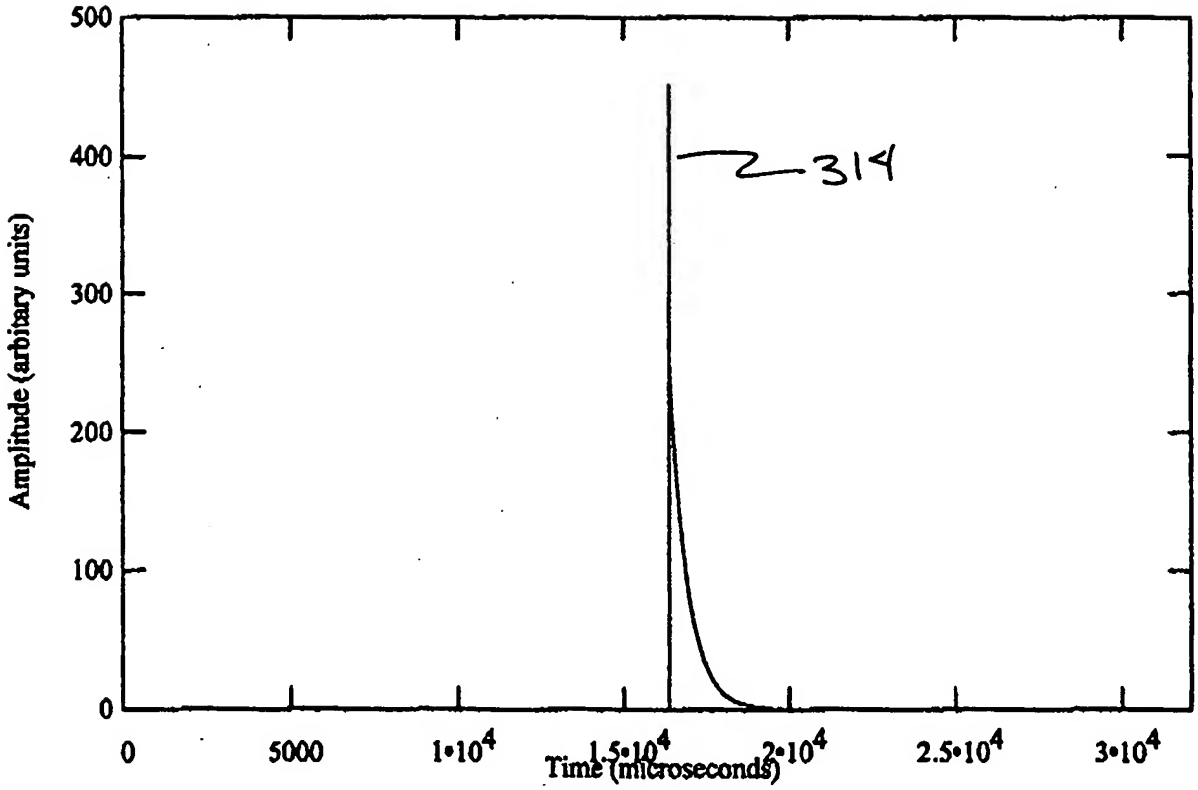
500
400
300
200
100
0
Amplitude (arbitary units)
2-314
0
5000
1•10^4
1.5•10^4
2•10^4
2.5•10^4
3•10^4
Time (microseconds)

FIG. 11

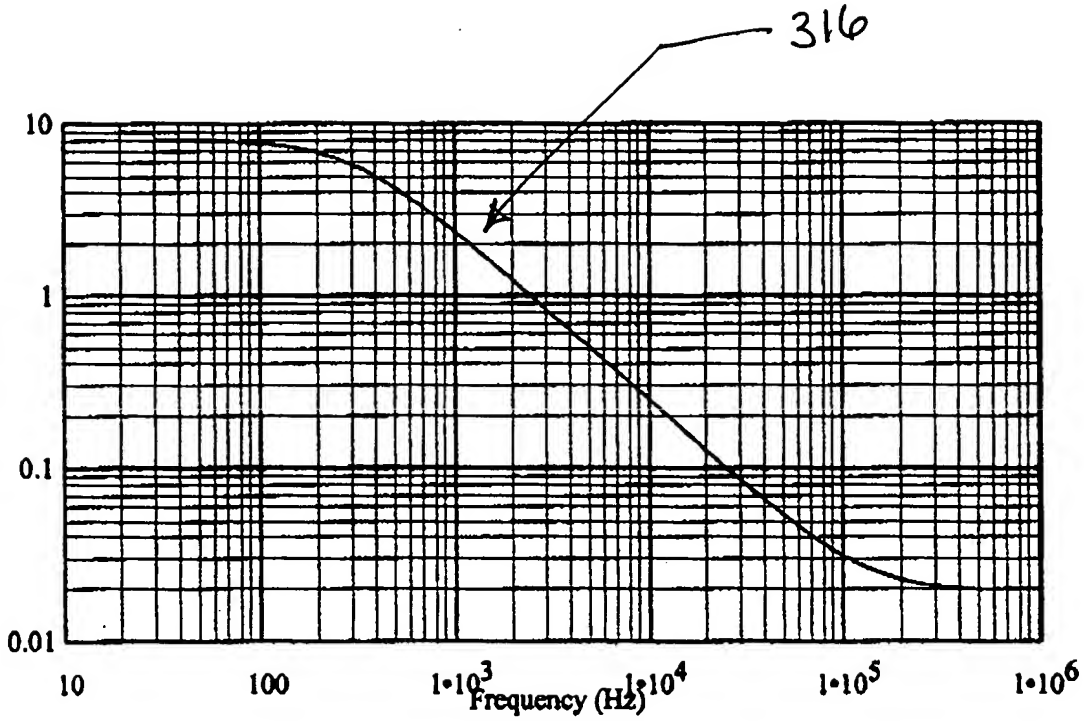
316
10
1
0.1
0.01
Amplitude (arbitrary units)
10
100
1•10^3
1•10^4
1•10^5
1•10^6
Frequency (Hz)

FIG. 12

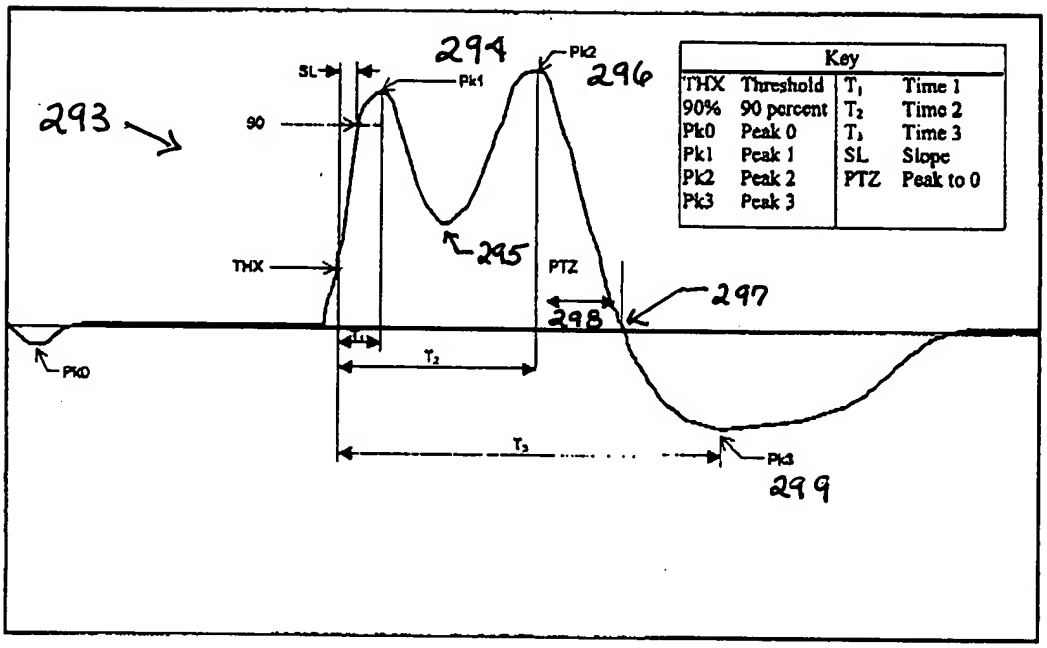
293
294
SL
Pk1
Pk2
296
90
THX
295
PTZ
298
297
Pk0
T2
T3
Pk3
299
Key
THX Threshold
90% 90 percent
Pk0 Peak 0
Pk1 Peak 1
Pk2 Peak 2
Pk3 Peak 3
T1 Time 1
T2 Time 2
T3 Time 3
SL Slope
PTZ Peak to 0

FIG. 13

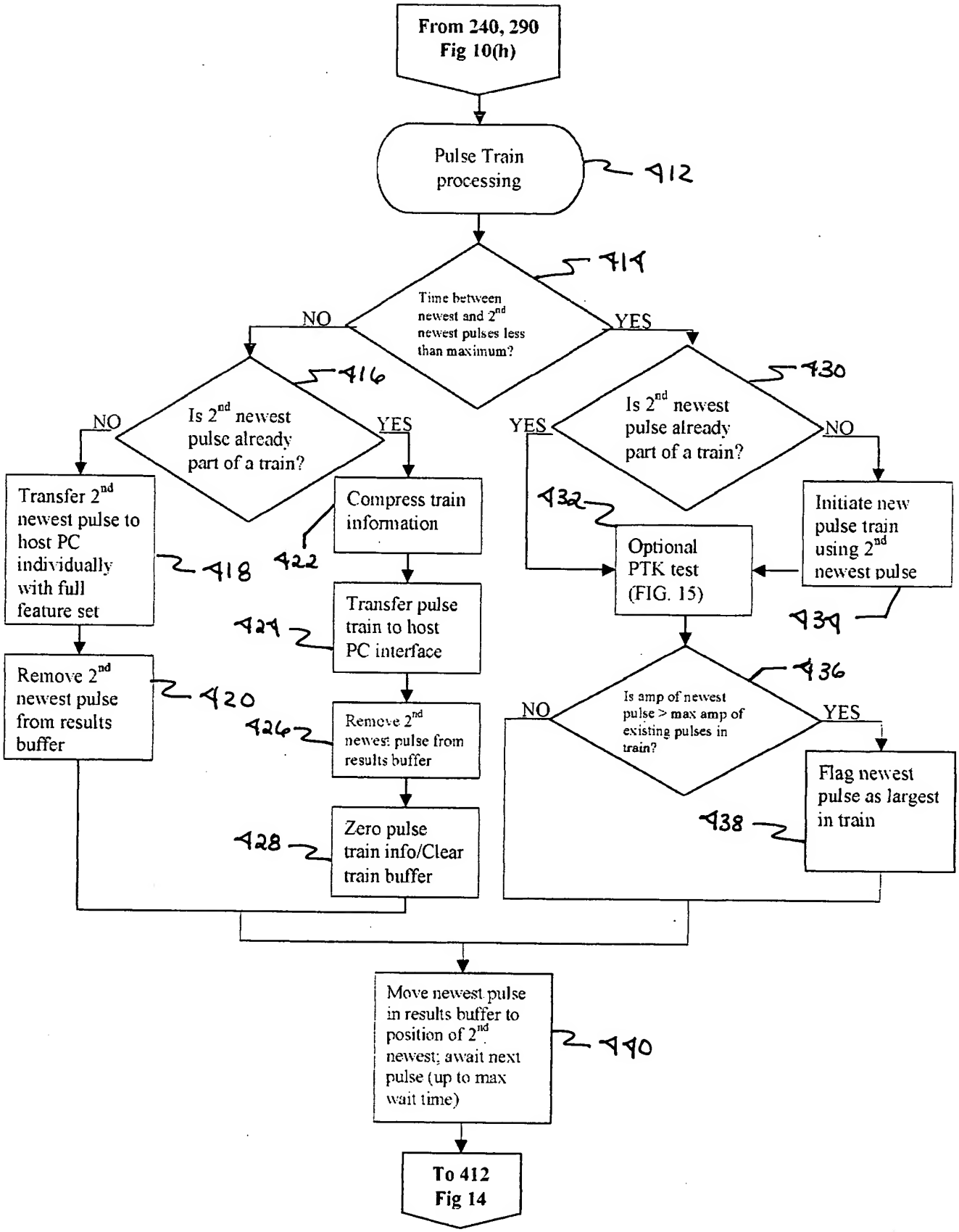
From 240, 290
Fig 10(h)
Pulse Train processing
412
Time between newest and 2nd newest pulses less than maximum?
414
NO
YES
Is 2nd newest pulse already part of a train?
416
NO
YES
Transfer 2nd newest pulse to host PC individually with full feature set
418
Remove 2nd newest pulse from results buffer
420
Compress train information
422
Transfer pulse train to host PC interface
424
Remove 2nd newest pulse from results buffer
426
Zero pulse train info/Clear train buffer
428
Is 2nd newest pulse already part of a train?
430
YES
NO
Optional PTK test (FIG. 15)
432
Initiate new pulse train using 2nd newest pulse
434
Is amp of newest pulse > max amp of existing pulses in train?
436
NO
YES
Flag newest pulse as largest in train
438
Move newest pulse in results buffer to position of 2nd newest; await next pulse (up to max wait time)
440
To 412
Fig 14

Fig. 14

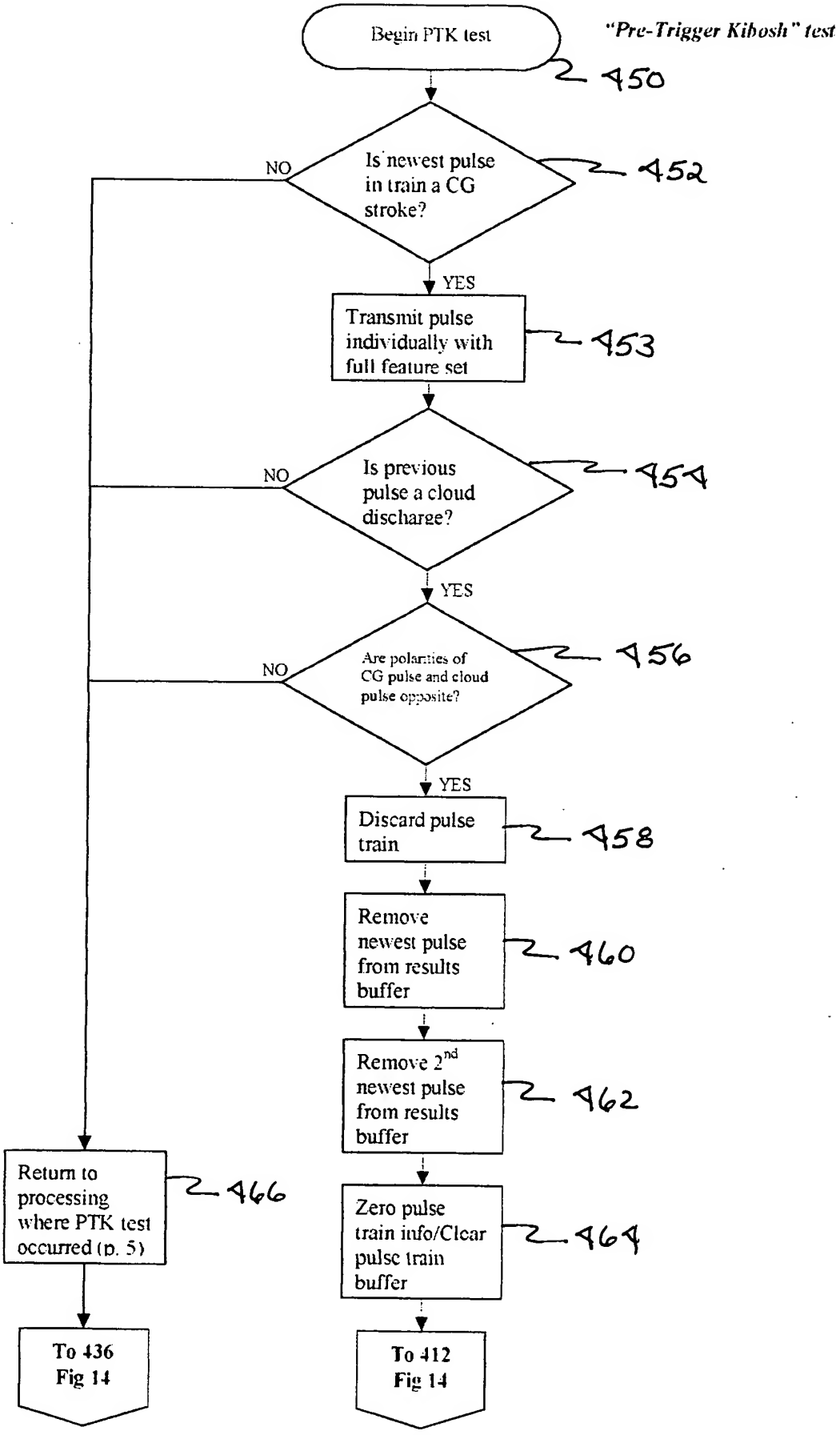
Begin PTK test
"Pre-Trigger Kibosh" test
450
Is newest pulse in train a CG stroke?
NO
452
YES
Transmit pulse individually with full feature set
453
Is previous pulse a cloud discharge?
NO
454
YES
Are polarities of CG pulse and cloud pulse opposite?
NO
456
YES
Discard pulse train
458
Remove newest pulse from results buffer
460
Remove 2nd newest pulse from results buffer
462
Zero pulse train info/Clear pulse train buffer
464
Return to processing where PTK test occurred (p. 5)
466
To 436 Fig 14
To 412 Fig 14

Fig. 15

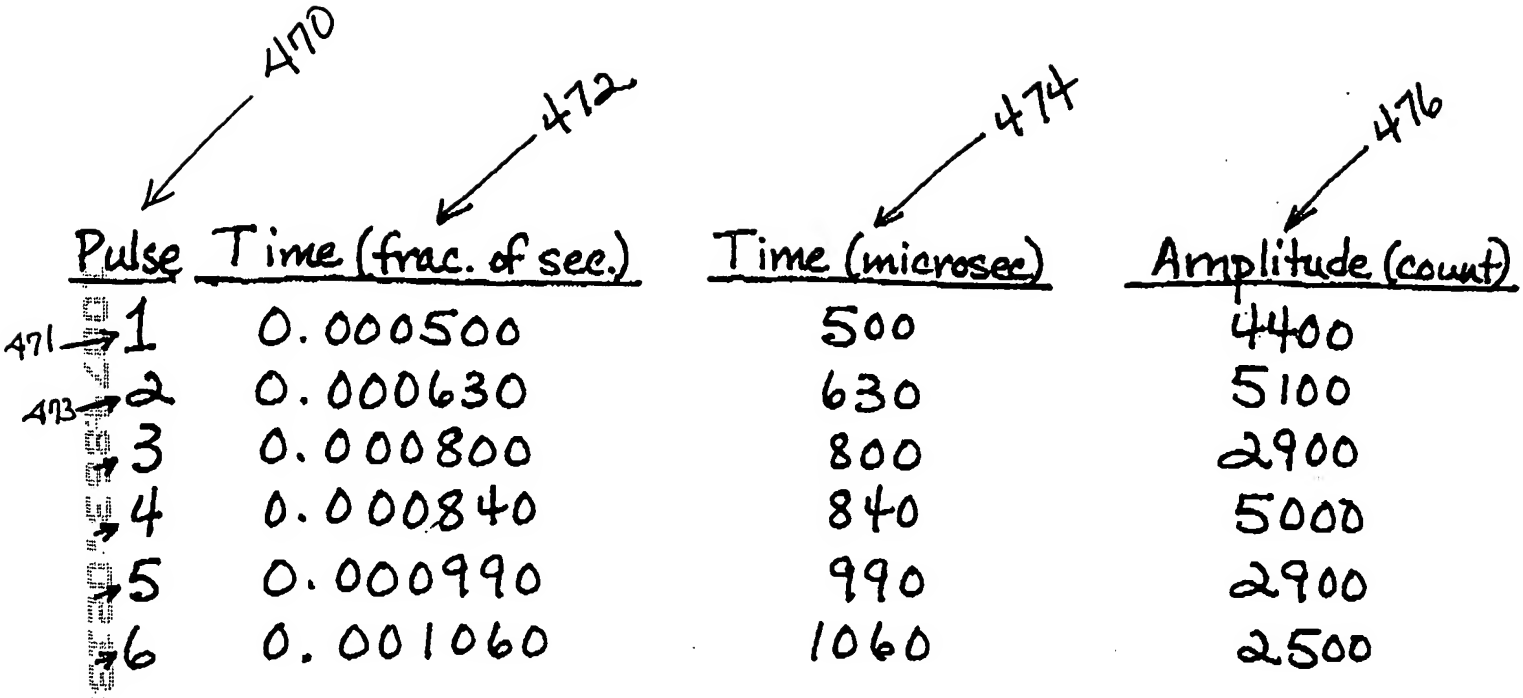
470
472
474
476
Pulse
Time (frac. of sec.)
Time (microsec)
Amplitude (count)
471
473
1
0.000500
500
4400
2
0.000630
630
5100
3
0.000800
800
2900
4
0.000840
840
5000
5
0.000990
990
2900
6
0.001060
1060
2500

FIG. 16

Complete representations — Decimal / Hexadecimal

Pulse 1	Time (to second):	997056000	3B6DDEØØ
	Fraction of second:	10000	271Ø
	Amplitude:	4400	113Ø
	Angle:	359.99°	7FFF
	Classification:	Cloud	1

471

480 482 484 486 488

FIG. 17

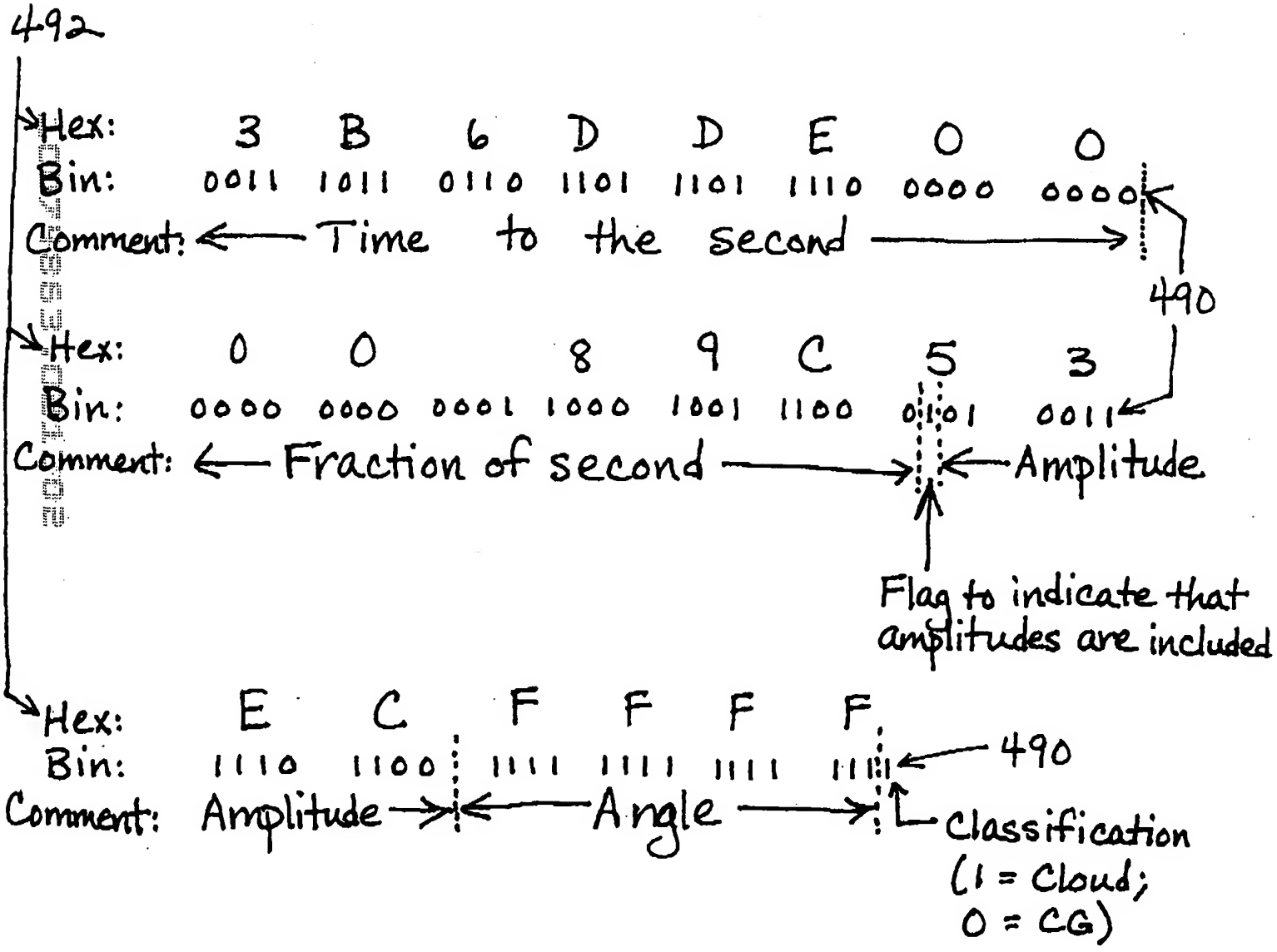
492
Hex: 3 B 6 D D E 0 0
Bin: 0011 1011 0110 1101 1101 1110 0000 0000
Comment: ← Time to the second →
490
Hex: 0 0 8 9 C 5 3
Bin: 0000 0000 0001 1000 1001 1100 0101 0011
Comment: ← Fraction of second → ← Amplitude
Flag to indicate that amplitudes are included
Hex: E C F F F F
Bin: 1110 1100 1111 1111 1111 1111
490
Comment: Amplitude → ← Angle → Classification (1 = Cloud; 0 = CG)

FIG. 18

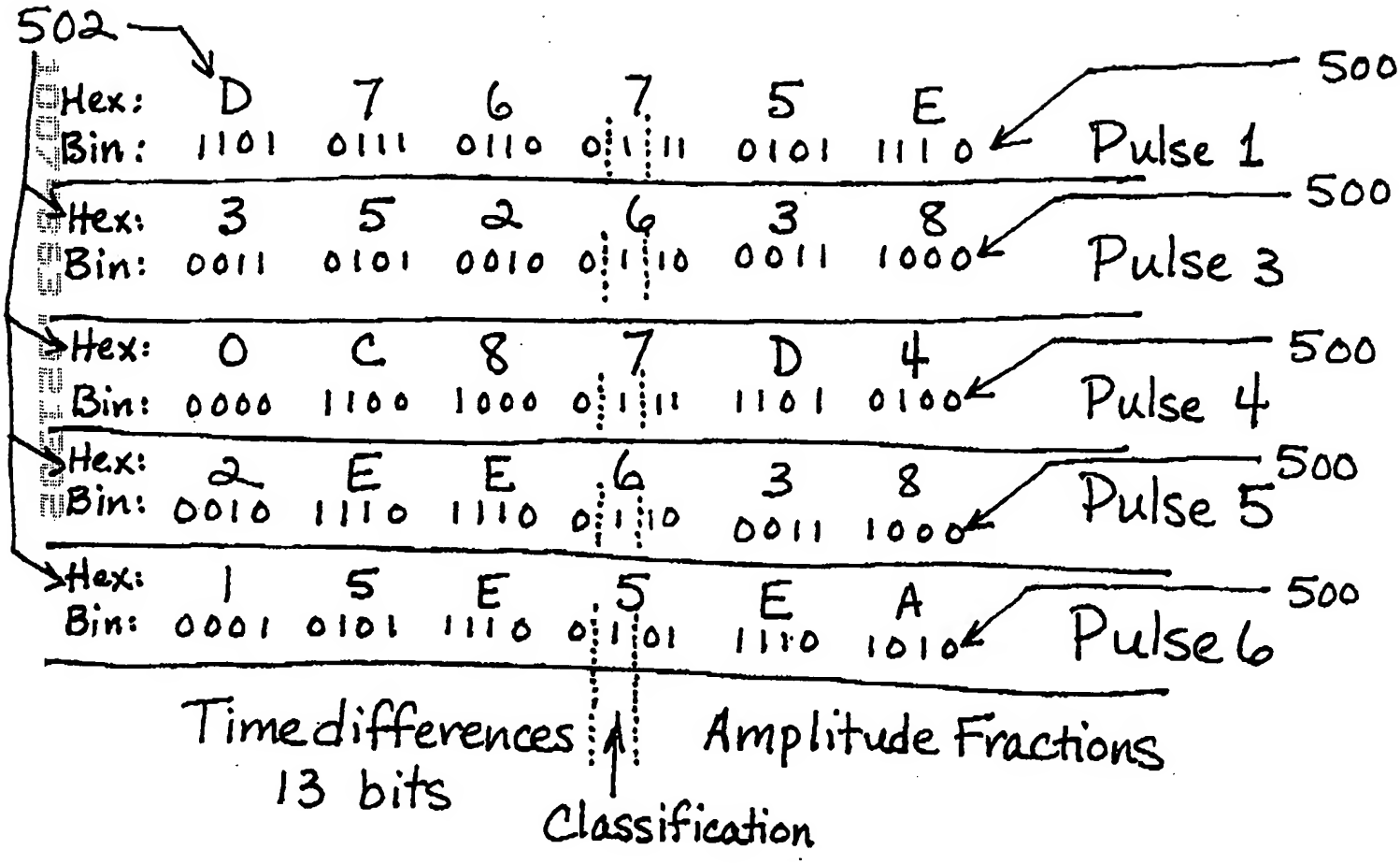
502
500
Hex: D 7 6 7 5 E
Bin: 1101 0111 0110 0111 0101 1110
Pulse 1
500
Hex: 3 5 2 6 3 8
Bin: 0011 0101 0010 0110 0011 1000
Pulse 3
500
Hex: 0 C 8 7 D 4
Bin: 0000 1100 1000 0111 1101 0100
Pulse 4
500
Hex: 2 E E 6 3 8
Bin: 0010 1110 1110 0110 0011 1000
Pulse 5
500
Hex: 1 5 E 5 E A
Bin: 0001 0101 1110 0101 1110 1010
Pulse 6
Time differences
13 bits
Amplitude Fractions
Classification

FIG. 19

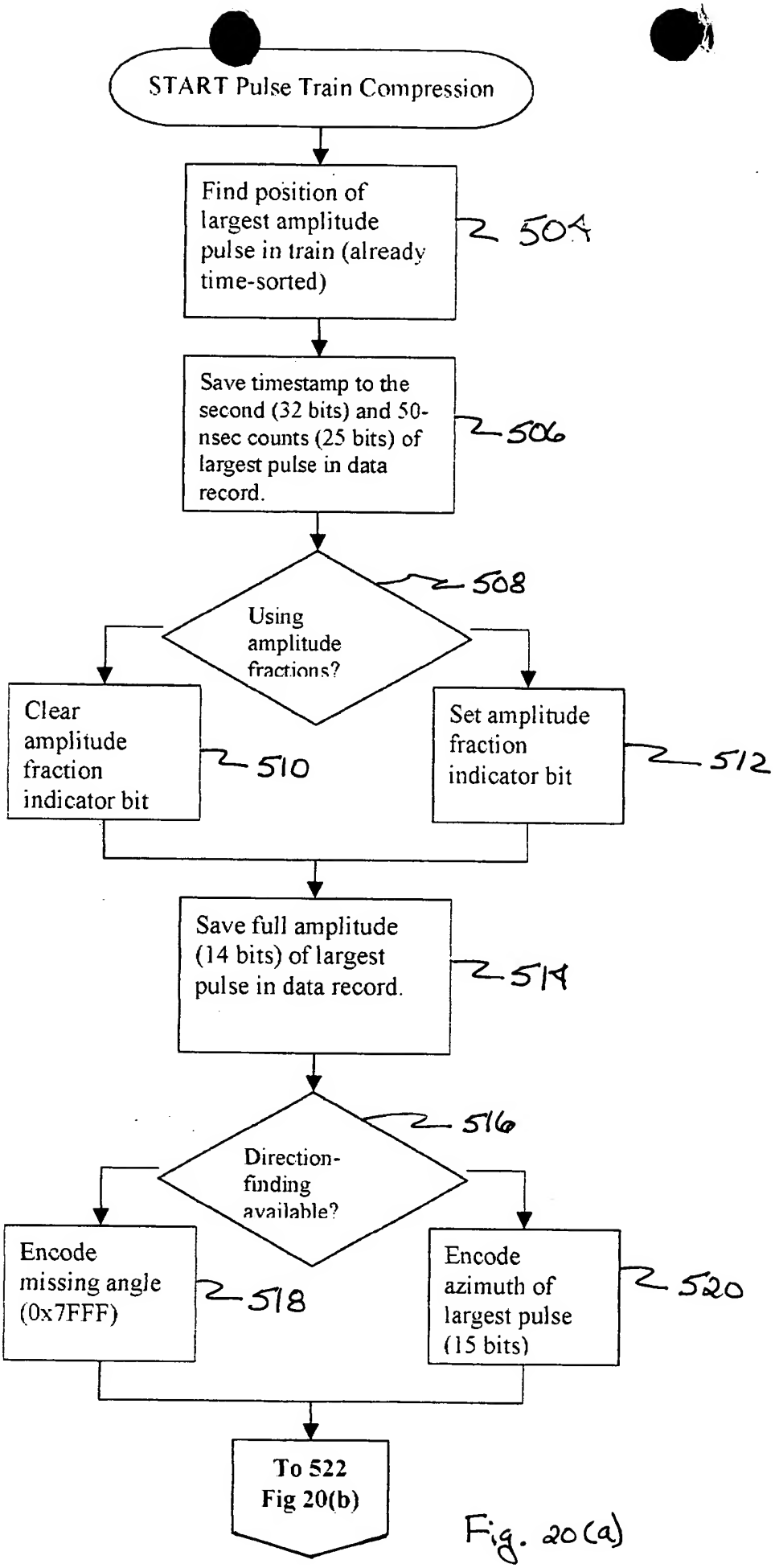
START Pulse Train Compression
Find position of largest amplitude pulse in train (already time-sorted)
504
Save timestamp to the second (32 bits) and 50-nsec counts (25 bits) of largest pulse in data record.
506
Using amplitude fractions?
508
Clear amplitude fraction indicator bit
510
Set amplitude fraction indicator bit
512
Save full amplitude (14 bits) of largest pulse in data record.
514
Direction-finding available?
516
Encode missing angle (0x7FFF)
518
Encode azimuth of largest pulse (15 bits)
520
To 522 Fig 20(b)

Fig. 20(a)

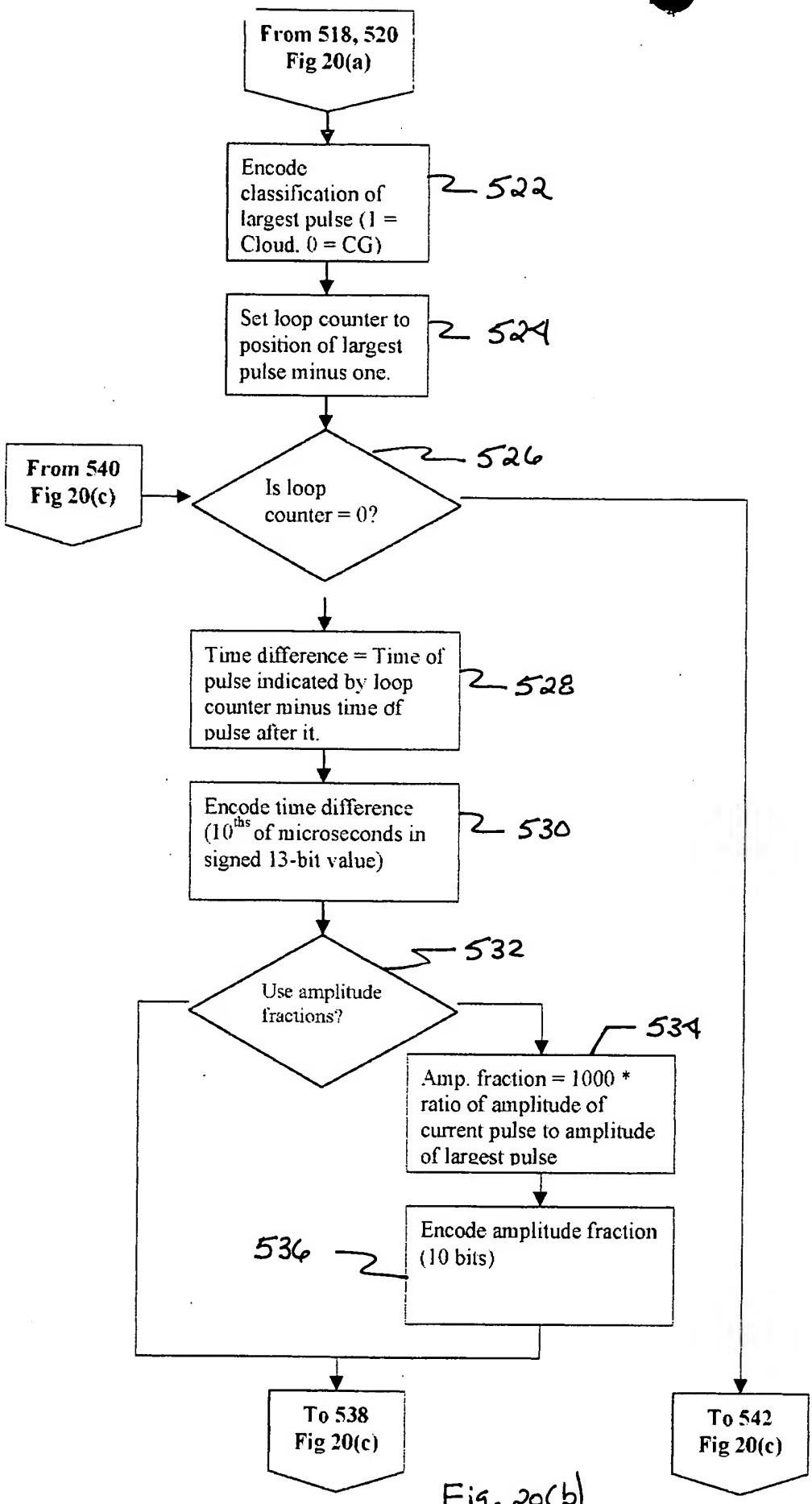
From 518, 520 Fig 20(a)
Encode classification of largest pulse (1 = Cloud. 0 = CG)
522
Set loop counter to position of largest pulse minus one.
524
From 540 Fig 20(c)
Is loop counter = 0?
526
Time difference = Time of pulse indicated by loop counter minus time of pulse after it.
528
Encode time difference (10^{ths} of microseconds in signed 13-bit value)
530
Use amplitude fractions?
532
Amp. fraction = 1000 * ratio of amplitude of current pulse to amplitude of largest pulse
534
Encode amplitude fraction (10 bits)
536
To 538 Fig 20(c)
To 542 Fig 20(c)

Fig. 20(b)

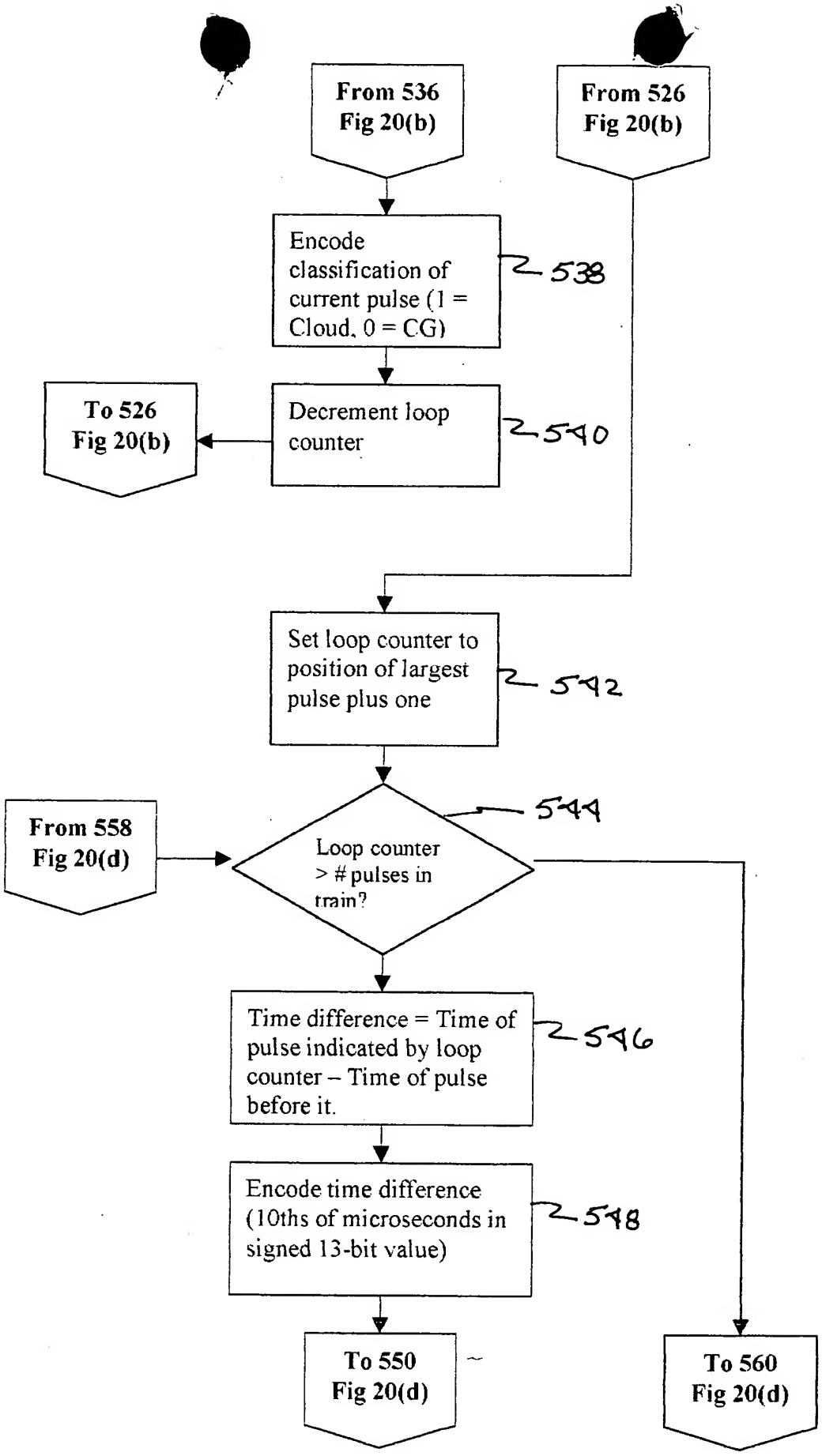
From 536
Fig 20(b)
From 526
Fig 20(b)
Encode classification of current pulse (1 = Cloud, 0 = CG)
538
Decrement loop counter
540
To 526
Fig 20(b)
Set loop counter to position of largest pulse plus one
542
From 558
Fig 20(d)
Loop counter > # pulses in train?
544
Time difference = Time of pulse indicated by loop counter – Time of pulse before it.
546
Encode time difference (10ths of microseconds in signed 13-bit value)
548
To 550
Fig 20(d)
To 560
Fig 20(d)

Fig. 20(c)

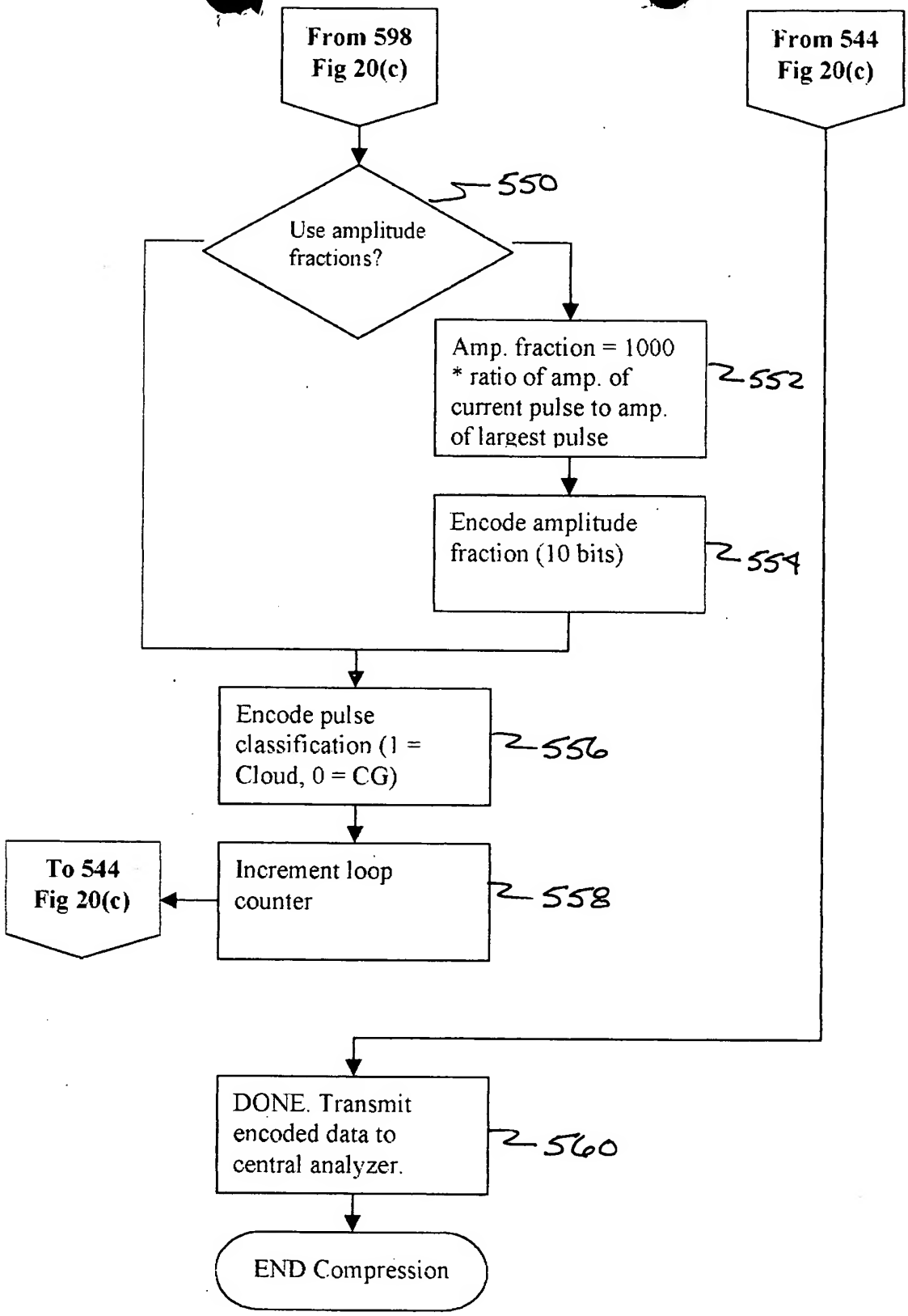
From 598
Fig 20(c)
From 544
Fig 20(c)
550
Use amplitude fractions?
Amp. fraction = 1000 * ratio of amp. of current pulse to amp. of largest pulse
552
Encode amplitude fraction (10 bits)
554
Encode pulse classification (1 = Cloud, 0 = CG)
556
To 544
Fig 20(c)
Increment loop counter
558
DONE. Transmit encoded data to central analyzer.
560
END Compression

Fig. 20(d)

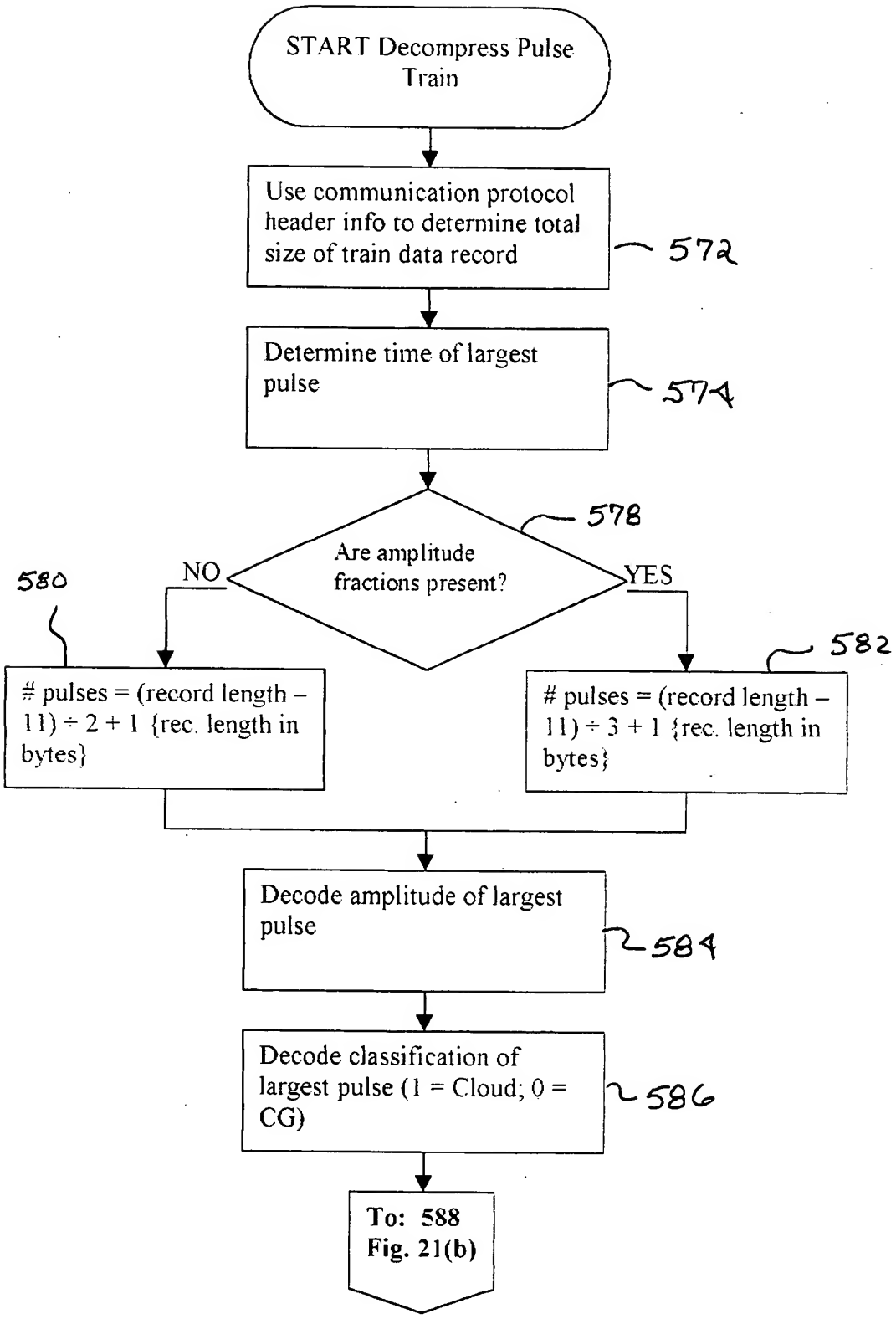
START Decompress Pulse Train
Use communication protocol header info to determine total size of train data record
572
Determine time of largest pulse
574
578
Are amplitude fractions present?
NO
YES
580
pulses = (record length – 11) ÷ 2 + 1 {rec. length in bytes}
582
pulses = (record length – 11) ÷ 3 + 1 {rec. length in bytes}
Decode amplitude of largest pulse
584
Decode classification of largest pulse (1 = Cloud; 0 = CG)
586
To: 588 Fig. 21(b)

Fig. 21(a)

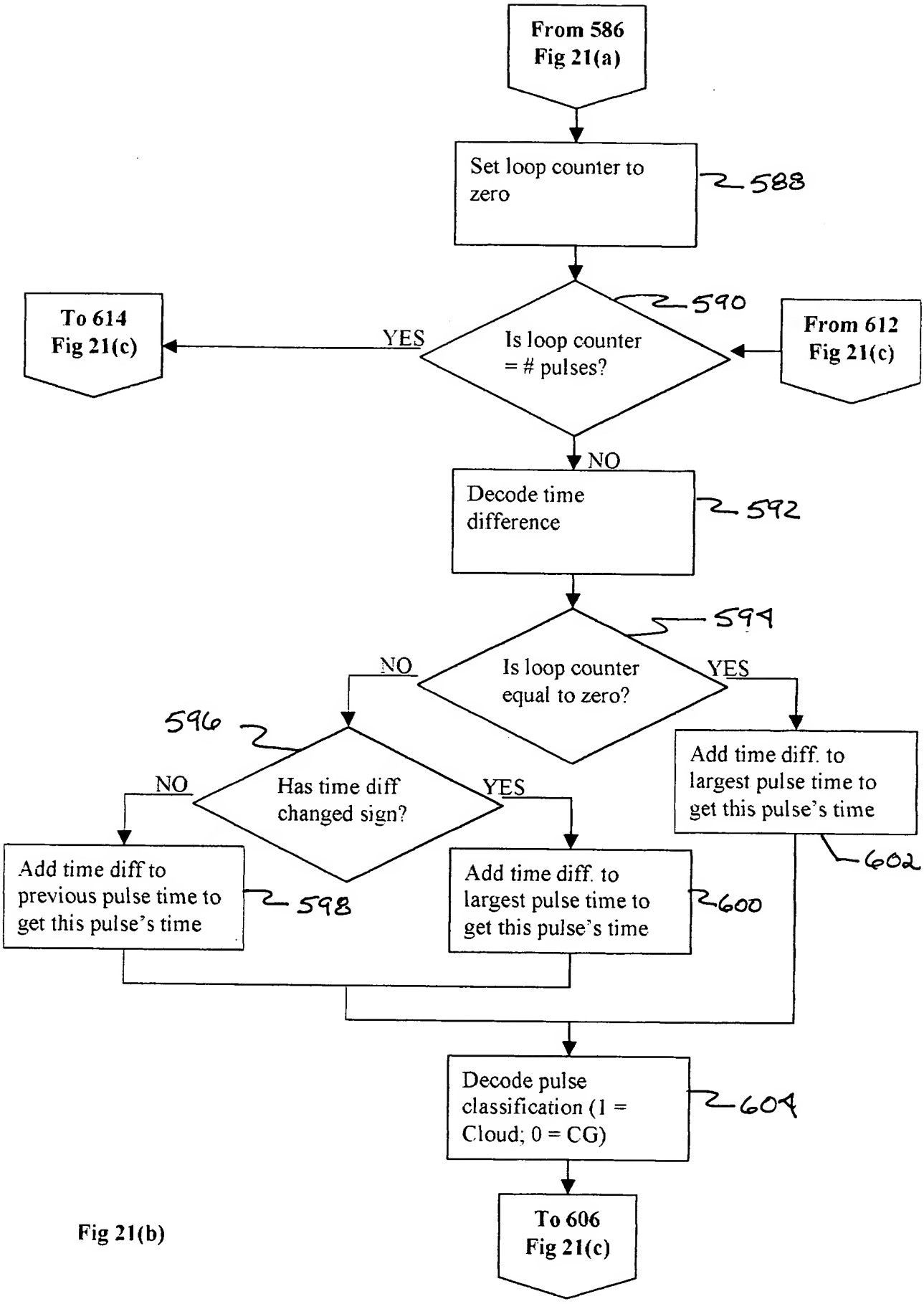
From 586
Fig 21(a)
Set loop counter to zero
588
590
Is loop counter = # pulses?
YES
To 614
Fig 21(c)
From 612
Fig 21(c)
NO
Decode time difference
592
594
Is loop counter equal to zero?
NO
YES
596
Has time diff changed sign?
NO
YES
Add time diff to previous pulse time to get this pulse's time
598
Add time diff. to largest pulse time to get this pulse's time
600
Add time diff. to largest pulse time to get this pulse's time
602
Decode pulse classification (1 = Cloud; 0 = CG)
604
To 606
Fig 21(c)

Fig 21(b)

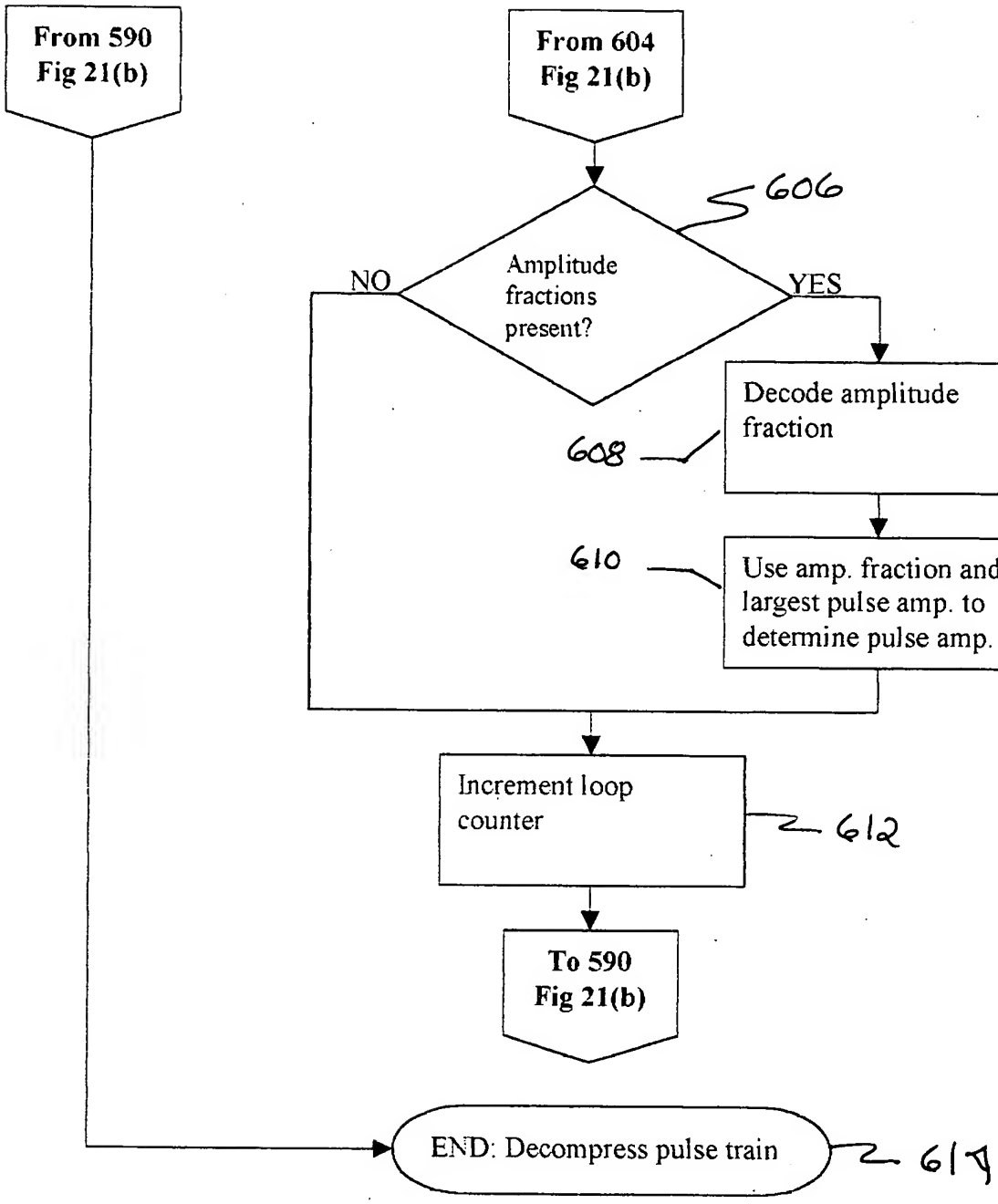
From 590
Fig 21(b)
From 604
Fig 21(b)
606
Amplitude fractions present?
NO
YES
Decode amplitude fraction
608
610
Use amp. fraction and largest pulse amp. to determine pulse amp.
Increment loop counter
612
To 590
Fig 21(b)
END: Decompress pulse train
614

Fig 21(c)

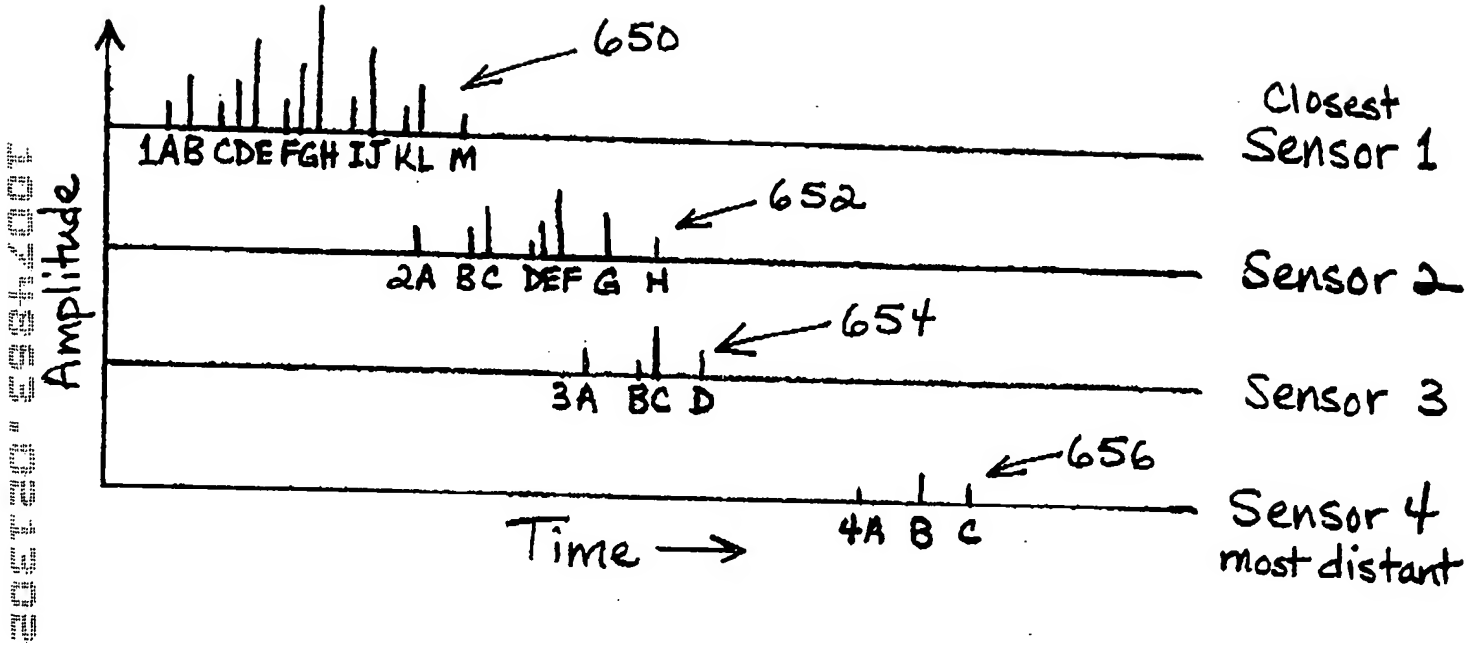
650
Closest
1AB CDE FGH IJ KL M
Sensor 1
652
2A BC DEF G H
Sensor 2
654
3A BC D
Sensor 3
656
4A B C
Sensor 4
most distant
Amplitude
Time

FIG. 22

SENSOR1	SENSOR2	SENSOR3	SENSOR4
1H	2F	3C	4B
1J	2G	3D	4C
1E	2C	3A	4A
1G	2E	3B	
1B	2A		
1L	2H		
1D	2B		
1F	2D		
1A			
1C			
1I			
1K			
1M			

DECREASING MAGNITUDE

FIGURE 23

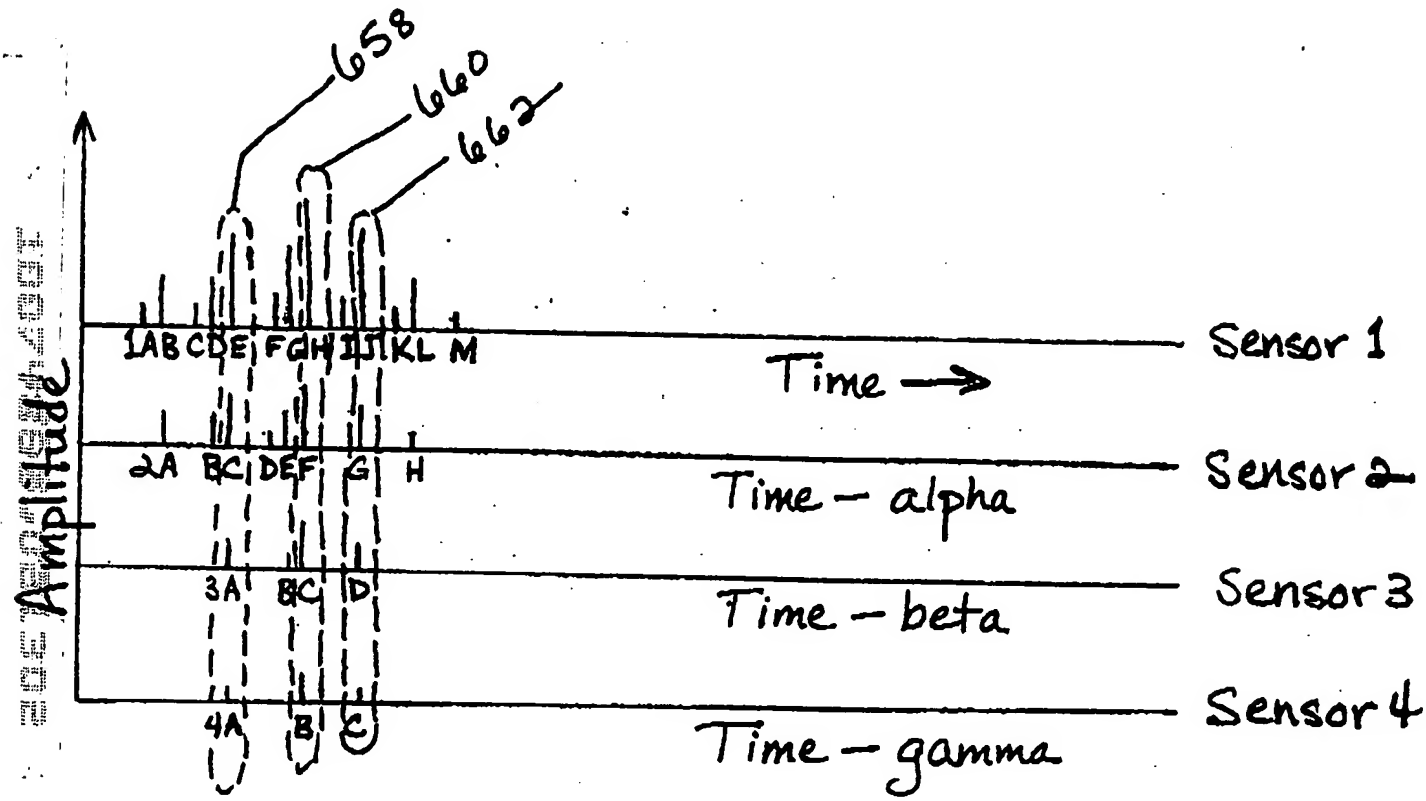
658
660
662
Amplitude
1A B C D E F G H I J K L M
2A B C D E F G H
3A B C D
4A B C
Time →
Time – alpha
Time – beta
Time – gamma
Sensor 1
Sensor 2
Sensor 3
Sensor 4

FIG. 24